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AN ENVIRONMENTAL OVERVIEW OF UNCONVENTIONAL EXTRACTION OF URANIUM

by

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This study was performed to provide information on the status of technological and environmental aspects of unconventional extraction of uranium for use by the Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency in developing research programs related to this method of uranium extraction.

Uranium mining areas in the United States are identified and briefly described, and the geologic, geochemical, and hydrologic factors associated with the various types of ore deposits are discussed. Uranium deposits that are now being mined or have recently been mined by solution-mining techniques are identified and briefly described; as well, deposits for which licenses have been obtained, but which thus far have not been mined, are listed.

The techniques used in these processes of uranium extraction are described and discussed. The environmental impacts specifically associated with these methods of extracting uranium are identified, using examples from case histories of in situ mining operations. Impacts on groundwater are of the greatest concern, and problems associated with these impacts are discussed. The major adverse impact is contamination from the effects of lixiviant chemicals. Restoration to acceptable post-mining conditions is a major concern and technical problem. Existing or proposed technologies to prevent or to control pollution from in situ mining of uranium are identified and discussed, with emphasis on the problems associated with groundwater.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report deals with the status of unconventional extraction of uranium ore including in-situ mining and, to a lesser degree, heap leaching. The purpose of this report is to determine the status of such extraction techniques so that a long term environmental research plan may be developed. Extraction techniques have been described, environmental impacts have been identified, case histories have been presented and areas of additional research have been recommended. This report should be of value to those individuals concerned about the environmental consequences of unconventional uranium extraction and those involved in such research. For further information regarding this report, contact the Energy Pollution Control Division.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This study was performed to provide information on the technological and environmental aspects of unconventional extraction of uranium. It is to be used by the Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency in determining the need for and, if necessary, developing research programs related to this method of uranium extraction.

Uranium mining areas in the United States are identified and briefly described, and the geologic, geochemical, and hydrologic factors associated with the ore deposits are discussed. Uranium deposits that are now being mined or have recently been mined by solution-mining techniques are identified and briefly described; also, deposits for which licenses have been obtained but which thus far have not been mined are listed.

The techniques used in uranium extraction are described and discussed. The environmental impacts specifically associated with methods of extracting uranium are identified using examples from case histories of in situ mining operations. Impacts on groundwater and problems associated with these impacts are discussed. The major adverse impact is contamination from lixiviant chemicals. Restoration of the mine site to acceptable post-mining conditions is a major concern and technical problem. Existing or proposed technologies to prevent or to control pollution from in situ mining of uranium are identified and discussed, with emphasis on the problems associated with groundwater.

Partial case histories of in situ mining operations are presented in order to describe instances of resulting degradation or non-degradation of groundwater quality. Information in this report also documents the development of monitoring and control technologies associated with in situ uranium mining. Specific problems and the actions taken to remedy them are described.

Research projects that address environmental impacts from unconventional extraction of uranium are identified. Also, areas of potential research are identified. The Federal and state laws which are applicable to unconventional extraction of uranium are listed.

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SECTION 1

INTRODUCTION

In situ uranium mining has resulted in a technology which is efficiently applied to the extraction of low-grade uranium deposits from permeable host rocks. This technology makes available as part of the national resources many such deposits that could not be economically mined by other existing methods.

The introduction of solvent chemicals, or lixiviants, into uranium-bearing geologic formations that are also reservoirs of groundwater causes severe deterioration of the groundwater quality; this constitutes the major environmental effect of the in situ mining operation. Included in the resulting negative effects are: the release of metals in toxic concentrations from minerals in the formation; the introduction of hazardous concentrations of materials in the lixiviants themselves; and the alteration of oxidation-reduction and pH conditions in the groundwater. Groundwater supplies may be locally depleted as a result of the operation.

Federal and state laws aimed at controlling the negative environmental effects of in situ uranium mining require that the groundwater in the mined zone be restored to near pre-mining conditions. Monitoring wells and water sampling and analysis programs are required to detect any excursions of the chemically altered groundwater outside the intended mine area. In most cases of excursions, differential pumping of the well field brings the excursion under control. In some cases, unexpected geologic features allow the fluids to breach aquitards. In others, failures of well structures permit leaks between formations.

Surface restoration to the required levels can be accomplished with relative facility. Restoration of the underground aquifer can be complex and time-consuming. This is particularly true in operations where lixiviants utilizing ammonium-based compounds have been used. This type of lixiviant is very effective in extracting uranium but sorbs to clay minerals and is not readily removed after the operation is completed.

Operators, regulatory authorities, and residents sometimes disagree what level of groundwater restoration is acceptable in return for the extraction of the uranium. Land use priorities, the demand for uranium and what constitutes pre-mining water quality are factors affecting these disagreements.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The information gathered for this project showed that a considerable gap exists between regulatory expectations and the ability of the industry both to comply and to carry out an effective minerals extraction program. Some operators have been unable to meet restoration requirements, while others have done so only after substantial effort and cost. Although much innovative work is being done to improve the technology, it appears that given the state-of-the-art, groundwater quality cannot be readily restored to pre-mining levels.

Realistic evaluation of the demands and utilization of groundwater should be considered when restoration criteria are established.

Materials and the technology to construct tight wells that will withstand the conditions of in situ mining are costly but will probably prove economic in the long term.

Detailed and realistic assessments of the fate of dissolved ammonium ions under deep groundwater conditions are also needed to determine the probability of nitrate formation and the health hazards associated with nitrates.

The development of a reagent that would promote the precipitation of dissolved contaminants, including ammonium, within the formation, without itself causing contamination would greatly facilitate groundwater restoration. Similarly, the improvement of lixiviant formulations and an improvement in the knowledge of metal solubilities under the special geochemical conditions of an in situ mine could decrease the contamination caused by associated minerals that are dissolved with the uranium. Until such technical developments occur, however, it appears that site-specific assessment of restoration criteria, in terms of land use priorities, may offer a potential for reduction of the difficulties encountered by many in situ operations.

Areas in which research is needed to provide better knowledge and control of the various processes associated with solution mining of uranium ore are described for exploration, environmental baseline characterization, well field and monitor wells, operation and restoration.

EXPLORATION

a) Means of adequately sealing exploration borings to prevent the inter-aquifer transfer of fluids. In the in situ mining industry and in the groundwater exploration and development industry in general, there is ample and widespread evidence that improperly cemented wells are responsible for breaches in aquicludes that would otherwise act as impermeable barriers to the movement of groundwater. The standardization of techniques that can be applied to remedy the further spread of this problem is of great importance to the control of leach-liquor excursions.

b) Knowledge of the extent of groundwater pollution associated with present drilling practices. In order to fully understand baseline water quality at a given site, it is important to know how much disturbance to natural values is caused by drilling and well completion activities, including the use of drilling fluid additives.

c) Development of means to obtain representative samples for the determination of water quality during exploration drilling. Because the numerical levels of control parameters of water quality as applied to in situ mining are very small, the impact of erroneous values due to using the results from non-representative samples can be great. Procedures and equipment used in obtaining water samples during exploration should be designed to produce values representative of formation-water conditions, apart from the influence of the drilling operation.

d) Improvement of the capability to predict the mobility of trace metals and their probable concentrations in leach liquors, by the study of core samples obtained during exploration drilling.

e) Knowledge of the effects of the opening of exploration borings on oxidation-reduction potentials and groundwater quality in uranium orebodies. Where holes are closely-spaced, the effects of ventilating the formation water may cause significant changes in the ambient geochemistry.

ENVIRONMENTAL BASELINE CHARACTERIZATION

a) Refinement of various aspects of the procedures used to characterize groundwater quality in the vicinity of uranium orebodies. Though procedures for acquiring this information are generally well understood, additional studies directed toward optimum location of wells, well sampling, and analysis of data would probably prove beneficial in establishing reliable and representative baseline water-quality values.

b) Improvement of the capability of defining directional properties in aquifers and aquicludes in the vicinity of uranium orebodies, for optimum well field and monitor well design.

WELL FIELD AND MONITOR WELLS

a) Improvement of techniques of computer-aided well field and monitor well design, using directional properties of aquifers and aquicludes.

b) Improvement of design and construction techniques of wells, for maximum aquifer protection and cost-effectiveness. Several instances of excursions have been attributed to breakdowns in well integrity, due either to material or construction failure. Research and development in this area may produce results of direct benefit to the in situ mining industry.

c) Improvement of logging and testing methods for verification of well integrity.

OPERATION

a) Improvement of lixiviant formulations to minimize mobilization of trace metals attendant to the mobilization of uranium.

b) Improvement of processes to selectively remove trace metals from leach liquor during processing and regeneration.

c) Improvement of techniques for the definition and identification of leach liquor excursions. These might include geophysical methods.

d) Development of methods of pretreatment of the ore-bearing formation to minimize problems of contamination resulting from the in situ mining operation.

e) Improvement of techniques for extracting hazardous wastes from the leach-liquor stream, in order to minimize the volume of waste and to maximize the volume of reinjected water.

RESTORATION

a) Development of treatment techniques to remove mobilized trace metals from solution in the formation.

b) Improvement of knowledge of the fate of ammonium and other nitrogen compounds under deep, mineralized aquifer conditions, and the associated health-hazard implications.

c) Study of the feasibility for permanent isolation of production zones from the rest of the aquifer by grouting or other artificial means, to prevent the spread of contaminants after completion of mining, as an alternative to complete restoration.

d) Evaluation of aquifer restoration criteria, in light of pre-mining acceptability of groundwater, potential future use, and alternative potable groundwater sources.

e) Evaluation of existing criteria and development of standards for long-term monitoring of sites mined by in situ leaching.

SECTION 3

EXTRACTION TECHNIQUES

3.1 INTRODUCTION

In situ and heap leaching of uranium are alternative methods of metal extraction which only minimally disturb the host rock but utilize moving fluids that pass through the rock, dissolve the uranium, and transport the dissolved metal to a collection and concentration site. In situ leaching of unmined rock may be applied to low-grade deposits situated below deep overburden, with relatively little impact on the original surface and subsurface of the mined site. The mining operation does not involve the removal of large volumes of bulk rock from the ground; hence it is not attended by continuous traffic of heavy vehicles, blasting, or dust clouds. No subsidence results from this method of mining, as only a very small proportion of the rock, usually intergranular and non-supportive, is removed. Because the method is based upon both the chemical and physical alteration of groundwater conditions, the major and most immediate environmental effect of an in situ mining operation is on the ambient groundwater. Thus, the planning and operation of an in situ leach mine necessarily involves the observation and control of groundwater conditions. This is necessary to avoid both the loss of leached metal from the mine site and the contamination of underground water supplies that would otherwise be utilizable resources.

Basically, an in situ leaching operation includes 1) the design of chemical solutions or lixiviants that will dissolve the uranium-bearing minerals and transport the uranium through the host rock; 2) the installation of injection wells which are used to introduce the lixiviant to the uranium ore and to maintain an elevated hydraulic pressure in the pore spaces or fractures of the rock; 3) the installation of production wells which maintain a lowered hydraulic pressure and thereby cause the uranium-bearing solution to flow toward them. The solution is pumped up the production wells to a processing facility on the surface, where the uranium is extracted and the lixiviant is reconditioned for re-injection to the orebody (Figure 1).

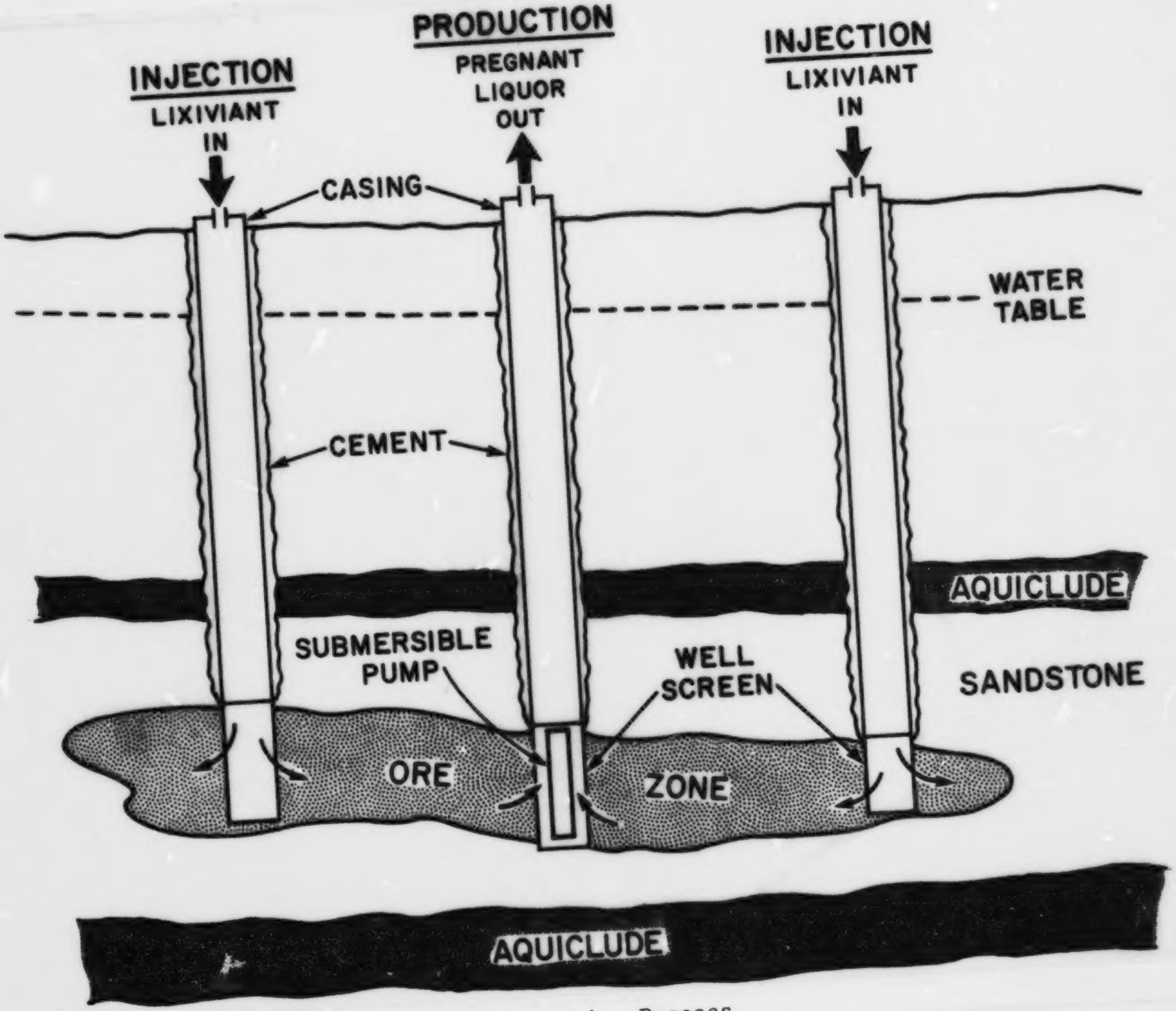
Continued movement of lixiviant through the orebody is necessary to remove the uranium. The amount of leaching necessary to achieve cutoff grade is clearly time-dependent and will vary with size of the orebody, solvent/mineral chemistry, permeability, and design factors associated with the well-field.

Licensing regulations require that groundwater be restored to or nearly to its original condition. Thus, the operation of the well field includes a period after production has ceased during which restoration must be accomplished.

3.2 SOLUTION, MOBILIZATION, AND EXTRACTION OF ORE

Lixiviants

The selection of a solvent for use in the leaching process must involve the consideration of the rate at which uranium minerals dissolve at the


INJECTION
LIXIVIANT
IN
PRODUCTION
PREGNANT
LIQUOR
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IN
CASING
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CEMENT
AQUICLUDE
SUBMERSIBLE
PUMP
WELL
SCREEN
SANDSTONE
ORE
ZONE
AQUICLUDE

Figure 1. In Situ Leaching Process

specific site, interaction of the solvent with non-ore minerals, effects on permeability of the rock, effects on well casings, pumps and other material of construction, cost availability, and handling problems (Huff, et al., 1980). Further, the ease with which toxic constituents of the solution can be removed from the mine site after production has ceased is of prime significance in the selection of a lixiviant.

The chemistry of uranium is such that its hexavalent form is soluble in either acid or alkaline leaching solutions. If the uranium in a particular deposit does not occur in the hexavalent state, it must be oxidized to that form by the use of an oxidizing agent (Kasper, et al., 1979). Thus, a lixiviant consists of two major components: 1) an acidic or a basic solvent to maintain a desirable pH range; and 2) an oxidant to convert tetravalent uranium to the hexavalent state and to maintain it in that state. Various combinations of solvents and oxidants may be used, depending upon conditions.

Only a few proposed in situ operations have been planned around the use of acidic lixiviants, and only two pilot operations have actually used acid. These operations utilized sulfuric acid, which is the least costly of the technically feasible acids. Oxidants that can be used in acidic lixiviants include sodium chlorate, manganese dioxide, ferric sulfate, and oxygen. Hexavalent uranium in the form UO_2^{++} is the soluble ion where acidic lixiviants are used; this forms an anionic complex with sulfate as follows:

$$UO_2^{++} + 3SO_4 \rightarrow UO_2\ (SO_4)_3^{==}$$

Rocks that contain large proportions of acid-soluble minerals such as calcite will consume significant or prohibitive quantities of acid solutions and hence are generally not suited for the use of acidic lixiviants. Also, reactions with phosphates, clay and oxide minerals may produce dissolved metal and other ions which present problems in regeneration of the lixiviant or in the potential contamination of water supplies.

Two types of alkaline lixiviants are commonly used, based on sodium carbonate-bicarbonate and ammonium carbonate-bicarbonate. In the solubilization process, uranium takes the form of uranyl tricarbonate anion, $UO_2(CO_3)^{-4}$. In clay-rich rock, swelling clays may make the use of sodium carbonate-bicarbonate solvents unfeasible, as decreased permeability and eventual plugging of the formation may result. The use of an ammonium carbonate-bicarbonate system, on the other hand, involves the possibility of sorption of NH_4^+ ions by clays and the formation of nitrates in groundwater. The use of either of the two carbonate-based solvents may result in the precipitation of calcium carbonate or the formation of free CO_2 gas, if the carbonate-bicarbonate equilibrium within they system shifts adversely. Potassium carbonate has also been used experimentally as an alkaline solvent, producing a potassium carbonate-bicarbonate system which is reported to be comparable in effectiveness to ammonium carbonate solvents. (Kasper, et al., 1979).

In alkaline solutions, the hexavalent uranium forms stable, complex anions which combine with ammonium or alkaline metals as follows (Cowan, et al., 1980):

$$UO_3 + 2NH_4HCO_3 \rightarrow (NH_4)_2\ UO_2\ (CO_3)_2 + H_2O$$

$$UO3 + Na_2\ CO_3 + 2NaHCO_3 \rightarrow Na_4\ UO_2\ (CO_3)_3 + H_2O$$

Alkaline solvents have an advantage over acidic solvents in that they react less with the country rock and their pH is therefore more stable. Acidic solvents tend to increase the permeability of the rocks through which they pass, but in so doing increase their pH. Sulfuric acid solvents may cause the precipitation of sulfates such a gypsum near the "downstream", or higher pH, end of the flow path, producing problems in wells, pumps, screens and other associated equipment. Oxidants used in the in situ mining of uranium are free oxygen and hydrogen peroxide. Of these, oxygen is perhaps the most commonly used, being cheapest. A disadvantage is that it may cause plugging of the formation or may migrate vertically. Hydrogen peroxide is more convenient to inject, but decomposes to produce oxygen in the formation. Its cost per pound of uranium produced is about 10 times that of gaseous oxygen (Huff, et al., 1980).

The uranium mining industry considers the oxidation phase of leaching to have a controlling influence upon the rate of leaching of uranium. Precise control over oxidant injection, relative to site-specific conditions, must be maintained in order to keep production at desired levels and to avoid wastage of oxidant through reactions with non-ore minerals. Thus, it is important to match oxidant and ore chemistry, and this match is achieved through field trials. Some laboratory techniques have been developed, however, which closely simulate down-hole conditions and provide design information early in the development of an in situ mine (Carlson, et al., 1980). The effects of oxygen and hydrogen peroxide, respectively, in an ammonium carbonate lixiviant were compared on samples of south Texas uranium ore. These tests indicated that desired initial high concentrations of oxidant can be economically achieved using a blend of hydrogen peroxide and oxygen.

Well Field Design and Operation

The design of the well field must be tailored to fit the conditions of the mine site. These conditions must be thoroughly understood prior to development, not only to optimize the mining operation but to comply with Federal and State regulations which require monitoring of the operation and post-production restoration. The boundaries of the orebody, its internal structure and grade variations, and geohydrologic factors must all be defined by a detailed subsurface geologic investigation. The development of the orebody is planned according to these defined characteristics.

The leaching and extraction of uranium under controlled conditions is basically a geohydrologic problem; therefore, a detailed analysis of hydrologic conditions at the site must be carried out. This may require studies of areal- or even regional-scale. Groundwater conditions must be defined in terms of depths, gradients, rates and direction of flow, veritical fluctuations, recharge and discharge, and relationships among individual aquifers and aquicludes. Test wells and laboratory analyses are used to determine porosities, permeabilities, rates of drawdown, and other hydraulic parameters of the ore zone or zones. The effectiveness of aquicludes in sealing off non-orebearing aquifers is also evaluated. Groundwater chemistry and its variations both vertically and laterally must be understood; it is equally important to understand the clay mineralogy of the formations involved, in order to forecast interactions among clays, lixiviants, and dissolved ions from the orebody and host rock. It is to the operator's benefit to carry out a very detailed evaluation of exisiting groundwater conditions, not only to provide better control for the design of the operation, but to supply information for use as a reference when post-production restoration is initiated.

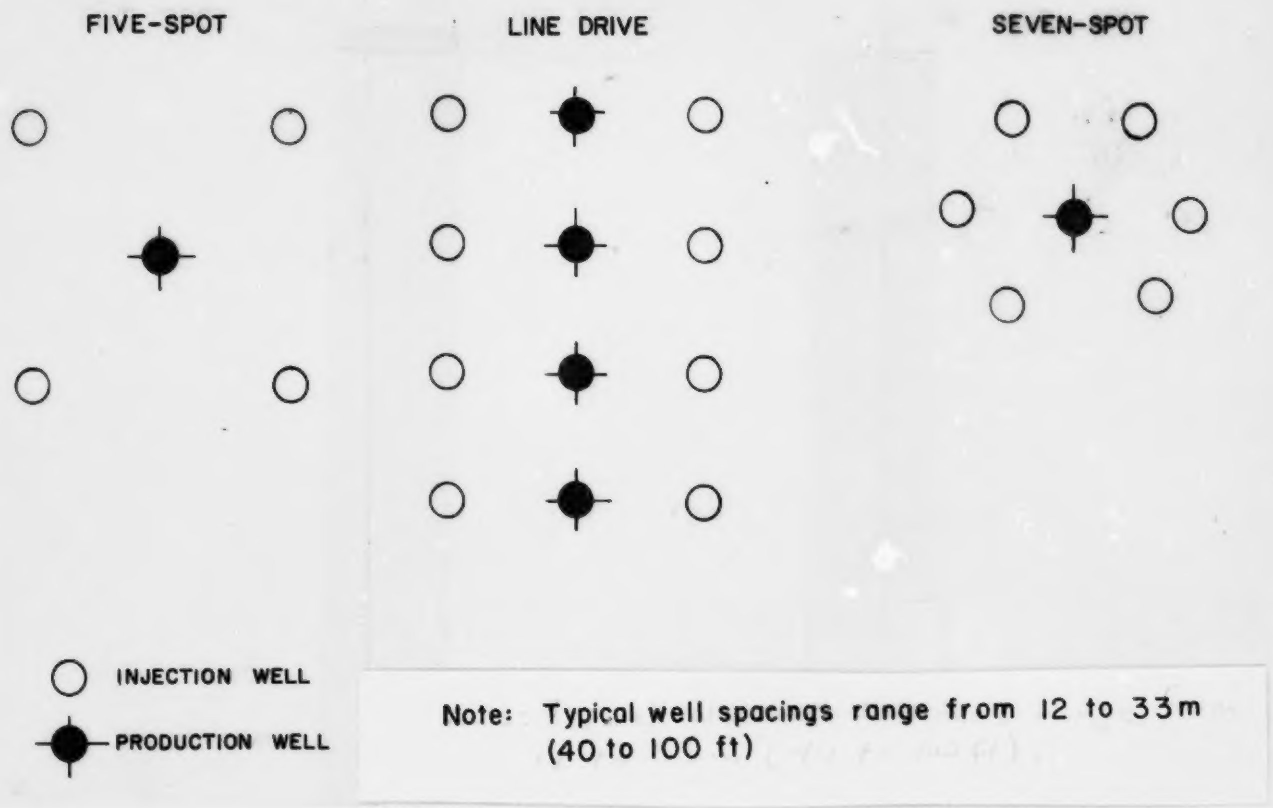
A typical well field consists of injection wells, production wells, and monitoring wells. Injection and production wells are arranged in patterns designed to provide optimum leaching and flow through the formation. A typical and widely used configuration is the 5-spot pattern, in which a single production well is surrounded by four injection wells. This and other commonly used patterns are depicted in Figure 2.

Ideally, all lixiviant introduced into the formation would be recovered by the production wells. In practice, the injected fluids move in directions other than toward production wells, and because of this, monitoring wells are placed around the mine site. These wells are designed to provide information on variations in groundwater properties outside the production zone that may be indictative of "excursions" or movements of solutions from the production zone outward or vertically into other groundwater zones. Monitoring of several parameters in these observation wells provides the information with which to control the flushing of the orebody. This process can be regulated by adjusting rates of injection and withdrawal. Monitoring also alerts the operator to problems of contamination of groundwater resources outside the permitted production zone.

In order to assure the hydraulic integrity of the injection well-orebody-production well system, the ore-bearing formation must be isolated from communication through the drill hole with underlying or overlying formations. This is accomplished through the use of a continuous casing between the surface and the production formation. The casing is perforated or terminated at the level of the production zone and is cemented in the hole with a cement that is formulated to be stable in the presence of the injected fluids.

Materials used in the casing must also be resistant to attack from lixiviants. PVC or fiberglass casing is commonly used in in situ mining operations. Where steel casing is used, inner liners of corrosion-resistant materials must be used to protect the steel, unless the considerably more expensive stainless steel is used. Pumps, valves, packers and other mechanical components of the system all must be chosen to withstand the corrosive effects of the solutions as well. Huff, et al., (1980) point out that engineering problems peculiar to the in situ mining industry include the difficulty of maintaining dispersion of gaseous oxygen in liquid solvents during the passage of the lixiviant down the injection well and the difficulty of obtaining downhole pumps for production wells that can withstand the ambient corrosive conditions over long periods of time.

When production is initiated, the orebody is flooded with injected lixiviant at elevated pressure. At the same time, withdrawal of groundwater is begun through the production wells at a slightly higher rate, setting up a hydraulic gradient that, ideally, causes the subsurface fluids to move from injection points toward withdrawal points. These relationships are illustrated diagramatically in Figure 1. Rates of injection and withdrawal must be adjusted to one another to ensure complete and continuous flooding of the production zone by the lixiviants, a residence time in the formation that will allow optimum use of the leaching capability of the lixiviant, without premature depletion, and the desired hydraulic gradients. The slight excess of production volume over injection volume, which is maintained in order to preserve a hydraulic gradient into the well field is called the bleed stream. Obviously, a major consideration in controlling passage of lixiviant through the orebody is the grade of recovered uranium at the surface, which must be sufficient over a defined time period to show a healthy profit margin for the mining operation.


FIVE-SPOT
LINE DRIVE
SEVEN-SPOT
INJECTION WELL
PRODUCTION WELL

Note: Typical well spacings range from 12 to 33m (40 to 100 ft)

Figure 2. Typical Well Field Configurations

Initially, production values should be low, as native groundwater is moved out of the production zone; as it is replaced by lixiviant, the uranium content of recovered liquid increases. As the production zone is flooded with lixiviant and a near-equilibrium flow condition achieved between the injection and production wells, the recovered uranium will maintain an essentially constant range of values. As leaching proceeds, recoverable uranium is gradually depleted and values begin to decrease, eventually reaching some level below which it is no longer economical to mine the deposit. The economics of in situ mining consider the number of pore-volumes (the total volume of displaceable fluid in the production zone) that must be exchanged to extract the ore-grade uranium. The number of pore-volume exchanges needed to deplete the deposit obviously will have a major influence on the life of the mine, while the time required to effect a pore-volume exchange is a function of many variable factors including hydrogeologic characteristics, number of wells, and pumping capacities. Fifteen or more pore-volume exchanges are expected to be required to recover the uranium values from Mobil's Mesquite Mine in Texas (Eng. and Min. Jour., Jan. 1981).

As ore is depleted from a given production zone, well patterns may be placed in new production zones in the orebody in order to maintain an acceptable overall grade of production for the mine. An orebody may be progressively mined over a predetermined period of time by staged depletion, in which new production zones are opened as old ones reach the cutoff grade for production.

Well spacing may vary with transmissive characteristics of the formation. Most host rocks for sandstone-type uranium deposits are anisotropic; it is therefore to be expected that internal fabrics, and hence transmissive properties, will vary directionally. Directional variations in flow velocities can be compensated for by adjusting the spacings between wells in such a way as to provide equal flow times from injection well to production wells, regardless of direction of flow. Typical spacings range from 12 to 33 m (40 to 100 feet).

At the Clay West Mine in Texas, 66 injection wells and 46 production wells are located within an area of less than 1.2 ha (3 acres). The wells are regularly-spaced on a 15 m (50 foot) grid pattern, with each production well being surrounded by four injection wells. A ring of monitoring wells surrounds the mine site at an average distance of about 61 m (200 feet).

Monitoring wells (Figure 3) are observed in order to detect fluctuations in physical or chemical parameters that might serve as indications of excursions or other alterations of ambient groundwater conditions. Such parameters might include changes in water level, conductivity, temperature, pH, and various chemical constituents such as sulfate, nitrate, bicarbonate, trace metals, and uranium. Generally, various permits issued by state authorities specify which parameters must be monitored. These specifications vary from mine to mine, and are usually determined on a case-by-case basis (Section 6).

Volumes of injected lixiviant vary with the size and transmissive properties of the production zone. At the Wyoming Minerals Comporation's Irigaray Mine near Buffalo, Wyoming, 50 L/s (800 gpm) were being injected into 200 wells in June, 1980 (Mining Record, 6-25-1980). The El Mesquite Mine, in Texas, is designed to handle 200 L/s (3200 gpm) in a total of 45 production areas, each of which is a complete well pattern.

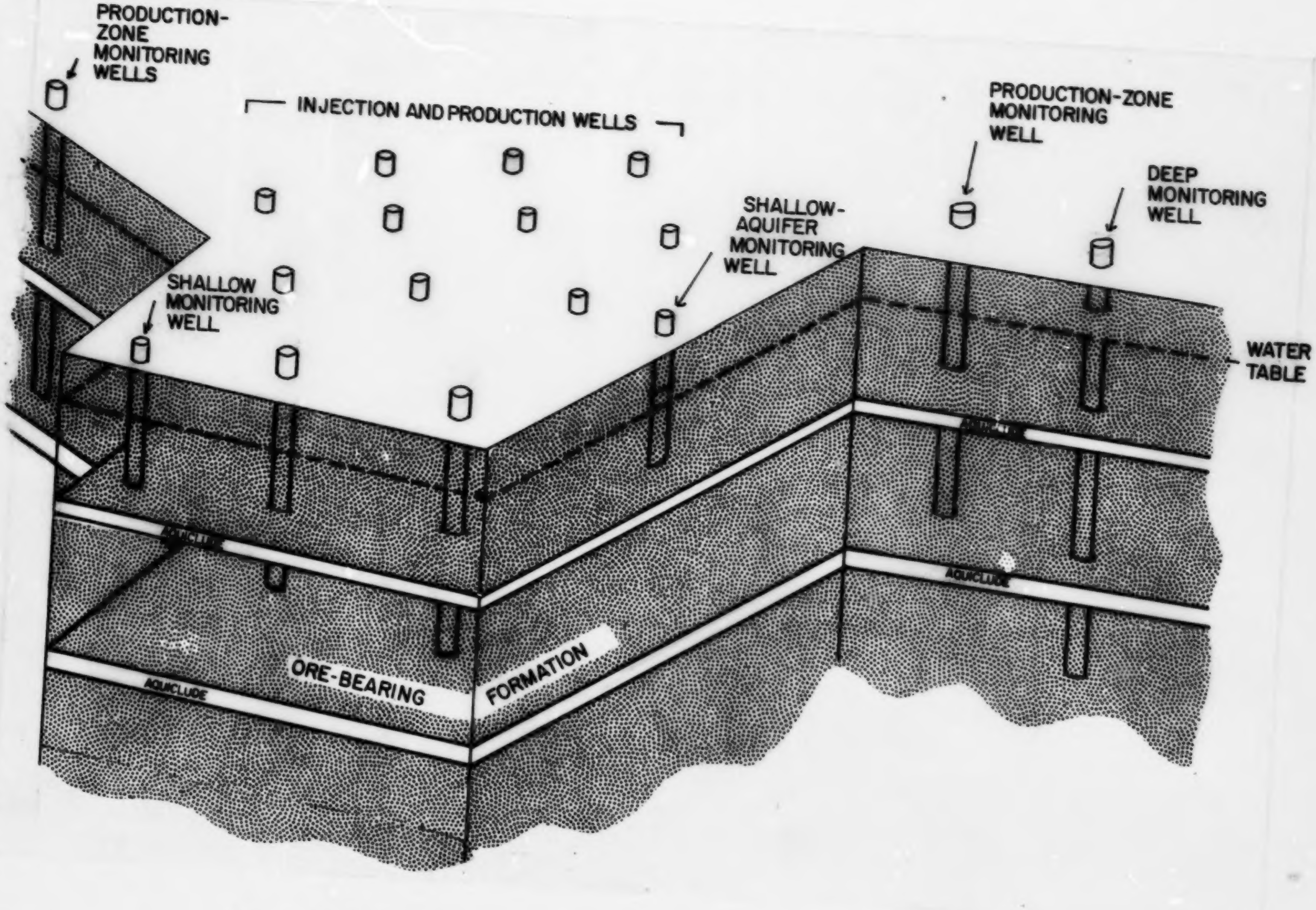

PRODUCTION-
ZONE
MONITORING
WELLS
INJECTION AND PRODUCTION WELLS
PRODUCTION-ZONE
MONITORING
WELL
DEEP
MONITORING
WELL
SHALLOW-
AQUIFER
MONITORING
WELL
SHALLOW
MONITORING
WELL
WATER
TABLE
AQUICLUDE
ORE-BEARING
FORMATION
AQUICLUDE

Figure 3. Mining and Monitoring Wells

In the event of an excursión of leachate or lixiviant into non-producing zones within an ore-bearing stratum, initial efforts to control the excursion consist of increasing the rate of production and decreasing the rate of injection. This produces an increased hydraulic gradient which tends to draw the excursion back toward the production zone. Experience has shown, however, that excursions into non-ore-bearing strata occur more often than those into strata being mined. Such excursions may be difficult to detect unless monitoring wells are proerly located in view of the stratigraphic and structural framework of the mine site. While these excursions may be due to natural features such as through-going fractures or discountinuities in aquicludes, they often are caused by leaky wells. Incompletely sealed cement plugs may allow vertical migration of fluids from the mined strata to other aquifers, while damage to PVC tubing by tools and samplers is a common source of leaks in the casing. In areas where considerable subsurface exploration has been carried out, unplugged exploration wells may also be a source of interformational leaks.

3.3 RECOVERY PROCESSES

The uranium-laden leachate, on reaching the surface through the production well, is pumped to a processing plant where the uranium is extracted and waste materials are separated out. In the plant, the leachate is passed through an ion-exchange resin in an extraction column. Here, the dissolved metal is retained in the resin, which at the same time releases displaceable ions into the leachate stream. When the resin has become "loaded" with uranium, it is transferred to an elution column where, by exposure to an eluant of suitable ionic strength, the uranium is displaced from the resin and the resin regenerated by the addition of (usually) chloride ions. The uranium concentrate from the elution column is then precipitated by the addition of a suitable reagent. The resulting uranium oxide is then filtered and dried to produce "yellowcake", U_3O_8. (Kasper, et al., 1979; Alvarez, 1980). Figure 4 depicts schematically these generalized steps in the process. The details of these steps vary from plant to plant; however, the flow lines and waste streams shown in the diagram are typical of all processing plants.

Waste streams are produced at the filter and drier, as the precipitate is separated from the eluant solution. At the extraction column, the leach solution, after losing its contained uranium to the resin, is returned to the well field for re-injection. Before this can take place, however, it must be renewed by the addition of fresh solvent and oxidant. Also, to avoid the recycling of dissolved ions which may descrease permeability by precipitation in the host rock, the water is processed through a purification unit before these renewal chemicals are added. Wastewater from both the extraction column and the purification unit is removed from the cycle. The compositions of the lixiviant and the minerals in the mined zone determine what types and amounts of dissolved materials remain in the leachate after the uranium is stripped from it. If significant quantities of heavy metals or toxic trace elements are present, special processing of the recycled leaching fluid may be necessary to control the increase of these materials in solution. This increase of dissolved toxic elements in the leaching fluid, through continued dissolution of the containing solid minerals, can have adverse environmental consequences.

The bleed stream, which is tapped off the leach circuit in order to maintain production at a higher rate than injection, is also a source of wastewater after it is processed.

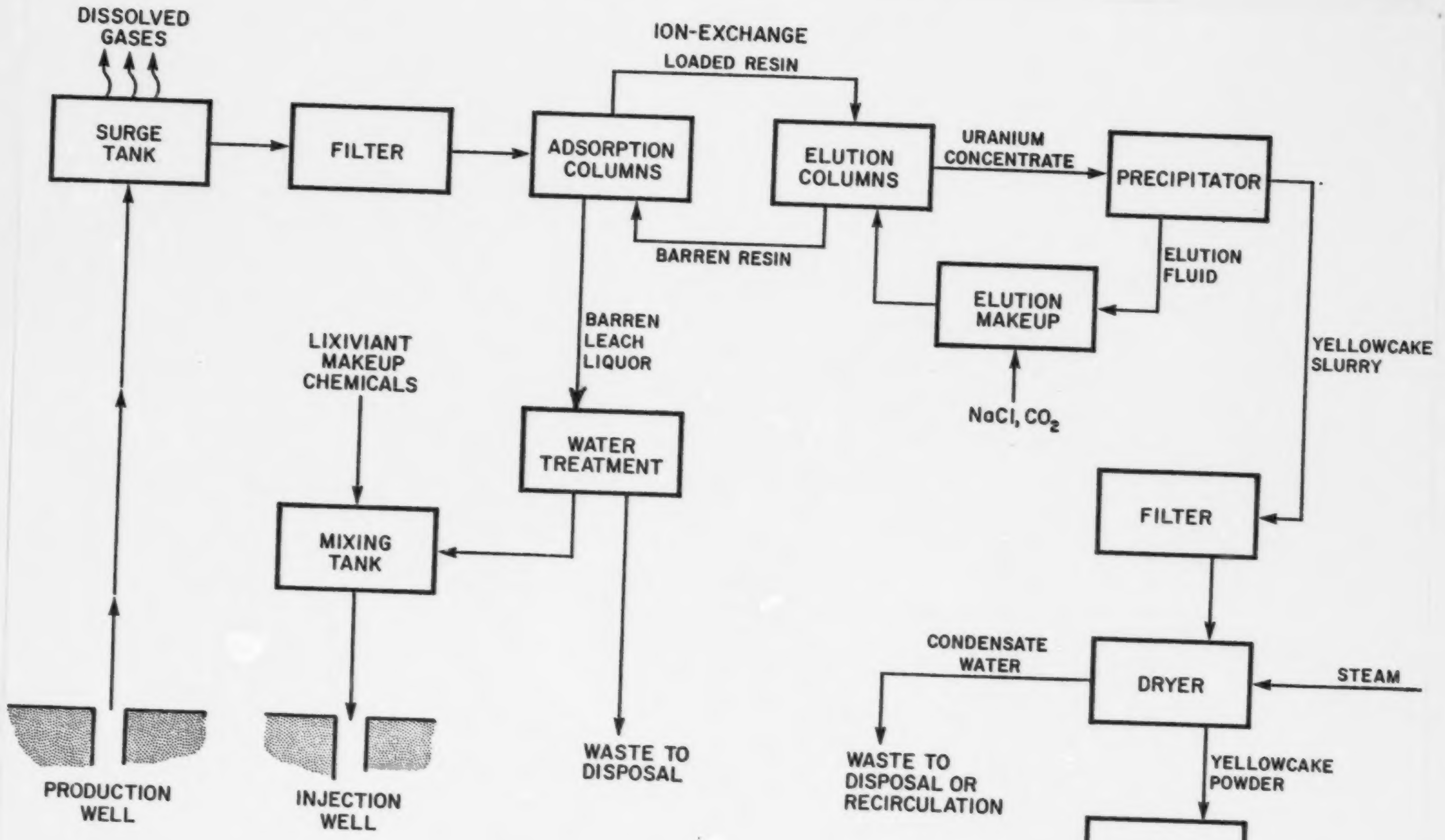

DISSOLVED GASES
SURGE TANK
FILTER
ADSORPTION COLUMNS
ION-EXCHANGE
LOADED RESIN
ELUTION COLUMNS
BARREN RESIN
URANIUM CONCENTRATE
PRECIPITATOR
ELUTION FLUID
ELUTION MAKEUP
NaCl, CO2
YELLOWCAKE SLURRY
BARREN LEACH LIQUOR
LIXIVIANT MAKEUP CHEMICALS
WATER TREATMENT
MIXING TANK
FILTER
DRYER
STEAM
CONDENSATE WATER
YELLOWCAKE POWDER
STORAGE
PRODUCTION WELL
INJECTION WELL
WASTE TO DISPOSAL
WASTE TO DISPOSAL OR RECIRCULATION

Figure 4. Ion Exchange Processing Plant

Wastewater from the production process is collected and stored for disposal through evaporation/concentration or deep well injection. Potential environmental problems are inherent in both of these methods, because toxic or radioactive materials may accidentaly be introduced to the air, the soil, or ground- or surface water during the disposal process. Various Federal and State regulations govern the design and operation of facilities that store or dispose of hazardous wastes. The effects of such facilities at uranium ore processing plants are discussed in Chapter 4.

3.4 PILOT PLANT PROGRAM

Regulatory agencies require that, prior to the issuance of an operating license for an in situ uranium mine, the applicant operate the plant on a pilot scale for a period long enough to demonstrate that lixiviant can be controlled, that any excursions can be remedied, and that satisfactory restoration can be achieved. Should problems be encountered during this pilot operation, modifications to the design of the plant may be made. Should irremedial problems occur, any negative environmental impact will be minimized due to the small area involved.

Pilot-scale operations are run over periods ranging from one to several years. The general practice is to mine the deposit for several months and then to restore the aquifer. Exxon's pilot plant in Valencia County, New Mexico, was expected (at startup) to operate for two months and to conduct restoration for nine months before the feasibility of a full-scale mine could be evaluated (Mining Record, 6-25-1980). Obviously, the cost of the pilot operation must be considered in evaluating the economics of a prospective in situ uranium mine.

During the pilot-plant test, the effects of mining the deposit are closely monitored, both to evaluate the efficiency of the operation and to detect any environmental degradation that may occur.

3.5 RESTORATION

Restoration programs are also an inherent part of the mining operation and must be included in the initial planning. They are conducted in response to regulations that require the operator to restore environmentally acceptable conditions to the in situ mine and surface site. Surface restoration can be accomplished with relative facility. Restoration of the underground aquifers affected by the operation, however, can be complex and time-consuming and is the major concern of the restoration program. Basic to the restoration program is the cessation of injection of lixiviant. Beyond that initial step, the approach to restoring the quality of affected groundwater may vary from mine to mine.

One alternative method that has been suggested involves natural physical and chemical processes which under near-neutral pH and in the absence of an oxidant, tend to result in precipitation and sorption of dissolved materials (Riding, et al., 1979). Other studies, however, suggest that oxidation-reduction conditions prevailing in groundwater of one ore-bearing stratum in Texas are not such that dissolved molybdenum (and, possibly, other metals) is removed by these processes (Henry, 1980); thus, this does not appear to be a universally applicable alternative but it has received attention by investigators (e.g., Buma, 1979). Some investigators (Riding, et al., 1979) believe that bacterial reduction and introduced chemical reductants such as hydrogen sulfide can be effectively used to restore groundwater. Natural restoration has not been demonstrated to be a viable method, nor has its use received approval from any regulatory agency.

Currently the most common approach to restoration is to flush the mined zone with clean water through the injection wells, extracting the altered groundwater through the production wells and processing it to remove undesirable constituents before re-injecting it. The continuous "rinsing" of the production zone with clean water was used to restore the pilot plant at Nine-Mile Lake, Wyoming, over a period of eight months (Engelman, et al., 1980). It is also planned as the major restoration method for several currently operating pilot plants and commercial-scale mines and at the Bruni and Palangana mines in Texas (Kasper, et al., 1979). Data presented by Kasper, et al., 1979 on the effectiveness of excursion cleanup demonstrations during pilot plant operations suggest that restoration may be accomplished in relatively short periods of time under some conditions. Molybdenum, sulfate, and conductivity values were all restored to within 95% of baseline values after 35 days of restoration efforts in those examples.

As displaced and diluted leachate is pumped to the surface, it may be treated by any of several processes to remove unwanted materials and to prepare it for re-injection. Reverse osmosis, electrodialysis, ion exchange, and distillation are among the available methods to accomplish this (Riding, et al., 1979). Ion exchange and reverse osmosis are presently the only feasible methods; ion exchange is utilized in the extraction of the uranium, while reverse osmosis has been used to treat wastewater prior to its disposal.

The separated hazardous materials must then be disposed of according to practices approved by regulatory authorities. Two proven methods for accomplishing this are deep well injection and solar evaporation ponds. Both methods require careful planning, engineering, and closure.

3.6 HEAP LEACHING

The technology of heap leaching as applied to the extraction of uranium is similar to methods developed for the heap leaching of other metals, such as copper. Essentially, heap leaching consists of passing solvents through piles of crushed, low-grade ore, tailings, or mineralized rock that was originally discarded as waste. The solvent solubilizes the metal and carries it in solution to a collection point. The liquor is then processed to remove the dissolved metal. Heap leaching is normally an above-ground operation and can be completely isolated from ground and surface water bodies by engineered structures. Thus, the threat of contamination of water resources by leach liquor is far less than it is in in situ mining. At the time of this writing, only six licenses were known to have been issued for heap-leach operations (see Table 24 in Appendix A).

The exact processes used in heap leaching uranium are highly proprietary and closely guarded by the companies that own them. Therefore, the example cited here as representative of heap leaching should be considered generally rather than specifically descriptive. This information was obtained from the public record, as part of material submitted in support of an application for an operating license (Cotter Corp., 1978).

In March, 1978, the Cotter Corporation, of Lakewood, Colorado, applied to the USNRC for a license to operate a pilot-scale test of a heap leaching process for the extraction of uranium (Cotter Corp., 1978). In the supporting documentation, the proposed operation was described.

The process is thin-layer (TL) acid leaching, developed by Holmes and Narver, Inc., of Anaheim, California. The purpose of the pilot operation was to evaluate the process in terms of economic production, using ore obtained from the Charlie orebody at Willow Creek in an open-pit mining operation. The ore occurred as uraninite and associated vanadates as coatings on sand grains, located along oxidation-reduction zone interfaces in sedimentary deposits of the Wasatch Formation. Approximately 6,000 to 8,000 tons of ore were exposed in the pit.

The process generally was to consist of crushing the ore, mixing it with a strong acid (93% H_2SO_4) and allowing it to "cure" in a specially-designed container for 16 to 24 hours. The acidized ore would then be transferred to a leach pad, where it would be washed with a weak acid solution for approximately 48 hours. The leachate would be collected and sent to a precipitation tank, where U_3O_8 and V_2O_5 would be precipitated by addition of MgO. After thickening and filtering, the yellowcake would be packaged for shipment. The plant was expected to have a daily capacity of approximately 25 tons.

The ore was to be transported to the mixing tank by conveyor belt, and, to minimize dust generation, was to be wet down by water sprays. For the same reason, the crusher and screens were to have dust hoods.

At the leach pad area, acid spray nozzles were to be placed below the grade of the pad. They were set to produce a coarse spray, in order to minimize acid mist generation. No acid spray effects were expected outside the leach pad area.

All liquid wastes were to be stored and treated before release or disposal. Accidental spills were to be contained by dikes. Disposal cells were to be lined with clay.

Seventeen batches, approximately 23 metric tons each, were processed in the pilot plant over a 46-day period in late 1979. Test data from samples collected during this period showed that concentrations of airborne uranium in various operating areas of the plant were two or more orders of magnitude below the allowable levels, and atmospheric radon levels in the vicinity of the pilot plant were one to two orders of magnitude below allowable concentrations (Cotter Corp., 1980).

Analyses of water draining from tailings produced some results that, according to the Cotter Corporation, were not representative of wastes from a commercial-scale plant. Table 1 presents concentrations of trace metals in samples from the above mentioned sample program. Cotter has stated that these more closely represent the projected characteristics affecting groundwater in the immediate vicinity of a saturated, below-grade tailings disposal cell.

No environmental problems had been reported from this operation in early 1981.

Table 1. Concentrations (mg/L) of Trace Metals and Inorganics, Willow Creek, Wyoming, Stage 2, Leach Potential Test (without clean water wash)

	Column No./Batch No.		
Chemical Parameters	1/1	2/1	3/2
Al	<1.0	<1.0	<1.0
Ca	84.0	80.0	80.0
Fe	<0.12	<0.12	<0.12
K	3.0	2.5	3.0
Mn	<0.05	<0.05	<0.05
Na	240.0	235.0	240.0
Ni	<0.15	<0.15	<0.15
U_3O_8	6.0	8.0	8.0
V	<1.7	<1.7	<1.7
Zn	<0.018	<0.018	<0.018
pH	8.21	8.29	8.23

Reference: Cotter Corporation, 1980

SECTION 4

ENVIRONMENTAL IMPACTS OF IN SITU AND HEAP LEACH MINING OF URANIUM

4.1 INTRODUCTION

The discussions in this chapter are focussed upon the environmental impacts inherent in the processes of solution mining of uranium and are not intended to cover all the environmental impacts that are associated with the setting up, operation, and dismantling of mines and mills in general. An in situ operation has some obvious environmental advantages over an open-pit or underground mine in that little or no dust, vibration, or objectionable noise is generated. However, due to its basic nature, this method of mining alters drastically the quality of groundwater at the mine site and can potentially contaminate surface or shallow subsurface water resources as a result of mill operations. Another major environmental concern is the release of radioactive substances from the mining operation.

Maintenance of water quality during and following in situ leaching of uranium is the fundamental problem which must be considered in an environmnental assessment of such operations. Prior to any leaching activity, a realistic baseline by which to judge groundwater quality must be established for any given operation. Monitoring programs will be required to evaluate subsurface restoration efforts and to assess the containment of the lixiviant and the solubilized ions within the mining area of the ore-bearing aquifer.

In the Grants, New Mexico, mining district, studies have indicated that major impacts on groundwater levels and flows will result from the extensive dewatering that is necessary to carry out a conventional underground mining operation (Stone, 1979). As in situ mining requires that the ore-bearing zone be flooded at all times, and as groundwater conditions must be restored after completion of mining, this impact is minimal or non-existent in a solution mining operation.

4.2 GROUNDWATER CONTAMINATION

Groundwater contamination may result from excursions of lixiviant from the production zone either laterally, into non-producing parts of the aquifer or vertically, into overlying or underlying aquifers and from increases in dissolved trace elements caused by the solvent action of the lixiviant and reactions between the lixiviant and the minerals of the formation.

It is significant that contamination in a solution mining operation is defined on the basis of the condition of the groundwater and not with reference to drinking water or other standards. Thus, the groundwater in the production zone before the lixiviant is introduced may not meet standards for potable water. Induced toxicities may therefore be increases in dissolved materials that were already considered toxic or otherwise unacceptable.

Table 2 presents compositional parameters for typical lixiviants. Table 3 lists compositions of leach liquors, as identified in analyses at typical mining operations (Kasper, et al., 1979).

Alteration of pH

Solvents used in lixiviants are designed to alter the pH of native water in orebodies to a range in which solution can take place efficiently. This results in strongly acidic or moderately alkaline pH values in the groundwater in the zone of influence of the injection wells. Reaction with minerals within the formation tends to neutralize the pH of the leach liquor, which may be maintained at desired levels by the addition of appropriate chemicals at the surface. Generally, water showing pH values outside the range of 6.5 to 8.5 is considered unsafe for drinking (US EPA, 1975). Excursions of lixiviant outside the bounds of the production zone may therefore result in undesirable or hazardous pH values in groundwater used for drinking. Restoration of pH baseline levels after intensive mining operations appears to require a relatively long time. In the pilot restoration program at the Nine-Mile Lake Mine in Wyoming (Engelman, et al., 1980), where a sulfuric acid lixiviant was used, flushing with native groundwater over a period of seven months resulted in a pH of 6.0, as compared to 6.8 in native groundwater outside the ore zone. The relatively slow recovery of this parameter is thought to be due in part to the presence of clay minerals above and below the ore body, which tend to retain sorbed H^+ ions and to release them gradually.

space

Introduction of Ammonium Ion

Where ammonium carbonate-bicarbonate lixiviant is used, ammonium ion presents a special problem in its impact on the subsurface environment. Most clay minerals have sites on or in the crystal structure which are occupied by ions sorbed to the clay by electrical bonds that are relatively weaker than the internal bonds of the crystal lattice. These ions are subject to replacement by other ions which are preferentially sorbed to the clay by bonds that vary in strength. Ammonium ion (NH_4+) has a strong affinity for clay and will be sorbed preferentially where strong concentrations are available (Degens, 1965). Sodium, calcium, and other cations may be displaced by ammonium ion, which is held by the clay during the leaching operation and given up only gradually during restoration. Adsorption of NH_4+ by clay in producing formations may result in concentrations in groundwater many times higher than baseline values. The presence of this ammonium is considered to be an environmental concern and permitting regulations require its reduction to acceptable levels. While these levels have not been determined yet, NH_3 levels of 10 ppm have been suggested for Texas mines (Yan, 1980). Natural waters in five Texas ore production zones had ammonia contents ranging from 0.01 to 2.1 mg/L, four of them being 0.2 mg/L or less (Table 4). Values were generally higher at three typical Wyoming study areas, in which ammonia concentrations were 0.1, 1.8, and 1.5 mg/L (Table 5).

Neither ammonium ion nor ammonia is considered to be toxic. Under cetain conditions, however, either of these compounds can produce nitrate ion (NO_3^-), small concentrations of which have been associated with metheglobinemia in infants. Because of this association and other health concerns, primary drinking water standards set the limit of acceptability for nitrate at 10 mg/L.

Table 2. Compositions of Typical Lixiviants

Concentrations of Typical Components of Acid Lixiviants

Component		Concentration Range (g/L)
Acid		
	Sulfuric Acid	3.0 to 20.0
Oxidant		
	Hydrogen Peroxide (50%)	0.5 to 2.0
	Oxygen	0.5 to 4.0

Concentrations of Typical Components of Alkaline Lixiviants

Component		Concentration Range (g/L)
Base		
	Carbon Dioxide	0.5 to 15.0
	Ammonia	0.2 to 5.5
Oxidant		
	Hydrogen Peroxide (50%)	0.5 to 2.0
	Oxygen	0.5 to 4.0

Modified from Kasper, et al., (1979)

Table 3. Typical Compositions of Leach Liquor

Partial Composition of Recirculated Acid Lixiviant

Constituent	Concentration (g/L)
Arsenic	0.05
Copper	1.00
Zinc	4.30
Lead	0.70
Manganese	1.20
Iron	25.40
Nickel	0.60
Chromium	0.15
Strontium	3.70
Zirconium	3.30
Vanadium	1.00
Cobalt	0.20
Ra-226	390 pCi/L

Partial Composition of Recirculated Alkaline Lixiviant

Constituent	Concentration (mg/L)
Arsenic	0.05
Copper	0.04
Zinc	0.10
Lead	0.20
Selenium	1.60
Iron	0.60
Nickel	0.06
Chromium	0.07
Molybdenum	0.90
Strontium	1.50
Zirconium	0.90
Ra-226	1750 pCi/L

Modified from Kasper, et al., (1979)

Table 4. Water Quality in Texas Ore Production Zones - mg/L Except pH, Conductivity, and Radon 226

Parameter	Location	A	B	C	D	E
	No. of Wells	15 wells	18 wells	3 wells	17 wells	5 wells
Calcium		42	52	80	267	14.5
Magnesium		9	10	11.6	68	2.9
Sodium		212	341	163	413	337
Carbonate		0	0	0	0	0
Bicarbonate		197	285	281	121	347.8
Sulfate		41	51	142	142	141
Chloride		280	436	143	1090	289.4
Fluoride		1.02	0.91	-	0.17	1.31
Nitrate		0.07	-	0.05	0.05	2.78
pH		7.94	7.6	7.3	7.4	8.05
TDS		699	931	764	2312	1052
Conductivity (F)		1281	1589	1310	3835	1154
Arsenic		0.003	0.074	0.01	-	0.2
Barium		0.1	0.2	0.5	0.05	0
Boron		0.53	1.2	0.57	0.19	2.15
Cadmium		0.001	0.0001	0.0025	0.007	0.01
Copper		0.007	0.004	0.015	0.007	0.64
Chromium		0.01	0.01	0.01	-	0.24
Lead		0.009	0.004	0.02	0.052	0.25
Manganese		0.01	0.02	0.046	-	5.06
Mercury		0.0001	0.0003	0.0001	0.0007	0.36
Nickel		0.02	0.03	-	0.037	0.01
Selenium		0.012	0.002	0.005	0.005	0.61
Silver		0.01	-	0.0023	0.007	0.1
Zinc		0.37	0.03	0.02	0.04	0.18
Ammonia		0.15	0.2	0.01	0.17	2.1
Uranium		0.07	0.1	0.181	0.15	0.17
Molybdenum		0.05	0.03	0.2	0.05	0.25
Vanadium		0.1	-	0.003	0.05	0.2
Radium-226(G)		96	349	274	19.2	52.3
Iron		0.02	2.6	-	-	2.06

A - TWQB Permit No. 02025, Dalco-U.S. Steel Burns Lease
B - TWQB Permit No. 01890, ARCO Clay West Mine
C - TWQB Permit No. 02050, IEC Pawnee Plant
D - TWQB Permit No. 01942, Wyoming Mineral Corporation Bruni Site
E - TWQB Permit No. 01941, Mobil Oil Corp. O'Hern Uranium Plant
F - Micromhos per centimeter
G - Picocuries/liter

Table from Kasper, et. al., 1979.

Table 5. Water Quality Data for Typical Wyoming Area Groundwater

Constituent/Site	A	B	C	D	E	F
Calcium	17	7.8	20.5	63	230	12
Magnesium	9.6	1.5	16	40	17	2.3
Potassium	2.5	7.3	7.9	-	-	-
Sodium	66	325	700	69	530	170
Bicarbonate	188	374	643	281	0.1	67
Chloride	9.0	12	21	8	360	51
Carbonates	0	7.4	120	-	170	18
Sulfate	14	202	880	130	950	220
TDS	288	917	1860	430	2300	560
Ammonia	0.1	1.8	1.5	-	-	-
Uranium	0.006	0.002	0.85	-	0.11	0.006
Selenium	0.003	0.005	0.22	-	0.01	0.01
Barium	0.5	0.5	0.5	-	1.0	1.0
Arsenic	0.01	0.02	0.02	-	0.01	0.01
Nitrate	0.05	0.85	0.32	-	0.62	0.18
pH	7.7	9.4	8.3	7.9	8.7	8.5

All concentrations are expressed in terms of mg/L except for pH.

Table from Kasper, et al., (1979).

Because nitrate ion in groundwater is very mobile, it is a major concern to the quality of water in aquifers. Nitrate can form from the oxidation of ammonium ion in a strongly oxidizing environment, where it is stable. In shallow groundwater bodies, a shift toward reducing conditions can lead to denitrification or breakdown of nitrate into nitrogen (N_2) or nitrous oxide (N_2O); these are innocuous in drinking water. Denitrification is promoted by a number of processes that are effective in shallow soil zones, including bacterial action, oxygenation, and heating. Denitrification below the water table, however, is incompletely understood. It appears that the scarcity of denitrifying bacteria in the groundwater may inhibit the conversion of nitrate to other forms. Theoretically, denitrification should occur in deeper groundwater under reducing conditions, producing N_2O, N_2, or ammonium ion (NH_4+) (Freeze and Cherry, 1979). Thus, it may be argued that under low-oxygen neutral-pH conditions, nitrate is unlikely to form from NH_4+ in deeper groundwaters. While highly oxidizing conditions are maintained[4] during the mining operation, restoration to baseline Eh values should result in a geochemical environment that does not favor nitrification of ammonium, so long as it remains in the restored formation. Further, in most situations, continued desorption of ammonium by ammonium-saturated clays probably would not result in widespread contamination of non-producing zone aquifers.
Transport of NH_4+ into areas of ammonium-poor clays should result instead in the fixation of the ion by resorption.

Mobilization of Metals

Sandstone-type uranium deposits are the result of precipitation of dissolved metals from groundwater, under conditions of changing Eh, from oxidizing to reducing conditions. Uranium and other metals with similar solubility are deposited together or in close proximity, often under the influence of reducing conditions brought about by the organic matter in the sediment. Therefore, alteration of ambient Eh and pH conditions to promote solubilization of uranium in this type of deposit unavoidably mobilizes other metals and introduces them into the leach liquor. Obviously, these dissolved metals vary greatly in composition and concentration from site to site, as they are dependent upon original mineralogy and the chemistry of the in situ mining operation; typical trace metals found in association with sandstone-type uranium deposits include selenium, lead, copper, nickel, arsenic, chromium, and molybdenum (Table 5), all of which are considered to be toxic above certain concentrations in drinking water. To reduce the potential for contamination of drinking water resources, permitting regualtions require that the dissolved metal content of formation waters be returned to defined levels near baseline values.

Table 4 lists the dissolved constituents in waters of typical orebodies of Texas, under natural pH and Eh conditions. Ideally, the flushing of lixiviant from the aquifer after completion of the mining operation should result in the restoration of these conditions and the consequent reduction and precipitation of metals that were mobilized during the operation. Recent studies, however, show that the behavior of dissolved trace elements that are mobilized under oxidizing conditions does not follow this predicted path, at least within a short time period. The reasons for this discrepancy between observed and predicted behavior are not understood; however, possible explanations include: (1) an incomplete understanding of thermodynamic relationships among these trace metals; (2) an incomplete understanding of all factors affecting solubility, including complexing by organic compounds; and (3) reaction times that are much slower than expected. Observation shows that some trace metals persist in the dissolved form even though they have been transported from mined areas into reducing environments (Henry, et al., 1980).

The restoration pilot program at the Nine-Mile Lake site, near Casper, Wyoming, required approximately 100 days of flushing to restore arsenic levels at one well to primary drinking water standards, while selenium values became asymptotic over a period of more than 200 days of restoration, reaching low values between 10 and 20 ppb (slightly above the standard of 10 ppb). A comparison of total dissolved solid values before and after the pilot restoration operation shows that restored values fall within measured concentration ranges inside the production zone but are slightly above values measured outside the zone (Table 6; Englemann, et al, 1980).

Other Salts from Leaching Solutions

In addition to ammonium, other components used in lixiviants and mill processes can build up concentrations in the groundwater that exceed baseline values and therefore must be restored by post-operational remedial actions. These components are discussed below.

Table 6. Groundwater Quality at Nine-Mile Lake, Wyoming, Comparison of Native, Preleach, and Restored Groundwater

	Native groundwater outside ore zone	Preleach pattern groundwater	Restored groundwater
pH	6.8	5.8-7.9	6.0
Free acidity	10	10	20
Calcium	110	20-360	65
Sulfate	1,620	300-3,600	2,200
TDS	2,660	680-5,450	3,000

All values in parts per million (except pH).

a) Sulfates--sulfate ion (SO_4+) is introduced to groundwater at sites where sulfuric acid is used as a lixiviant; however, it may also appear at sites where alkaline lixiviants are being used as a result of oxidation of pyrite or other sulfides under the induced highly-oxidizing conditions. Sulfate readily combines with calcium, which is commonly abundant in sedimentary rocks, to form gypsum. Sulfate in drinking water may cause gastrointestinal irritation, and the U.S. Secondary Drinking Water Standards accordingly set the acceptable maximum at 250 mg/L; however, this value may be exceeded by several multiples in natural waters, particularly those associated with concentrations of minerals. As an example, Englemann, et al., (1980), cite preleach sulfate concentrations of 300 to 3600 ppm in ore-zone ground water at the Nine-Mile Lake mine in Wyoming, while concentrations outside the ore zone averaged 1620 ppm.

b) Chlorides--this ion commonly enters the leach liquor streams at the extraction column, where it is used as the exchangeable ion in resins. Sodium chloride (NaCl) is the most widely used agent for regeneration of ion-exchange resins, as chloride causes only minimal interference with the leaching process (Kasper, et al., 1979). The U.S. Drinking Water Standard maximum for chloride is 250 mg/L. As this value is commonly exceeded in natural waters, it is in the mine operator's interest that a detailed baseline sampling program be carried out before lixiviants are injected.

Although the major effect of excessive chloride content on drinking water is aesthetic, in that an unpleasant taste is produced, Galloway, et al., (1981, p. 283) note that chloride may act as a complexing ion for base metals and hence should increase the solubility of those metals.

c) Total Dissolved Solids--Drinking water standards set the acceptable limit for total dissolved solids (TDS) at 500 mg/L; however, in many regions, groundwater used for drinking exceeds this limit and water from mineralized formations would commonly do so. Baseline values for groundwater at the Nine-Mile Lake mine were 2660 mg/L outside the ore zone and 680 to 5450 mg/L in the ore zone. As values of 1,000 to 3,000 mg/L are typical for uranium leaching operations (Kasper, et al., 1979), careful compilation of baseline data will provide for optimum differentiation between the effects of solution mining and the ambient chemistry of natural waters.

Leach Liquor Excursions

The possibility of an excursion occurring in an in situ mining operation is moderately likely. This possibility decreases with the degree of understanding of subsurface geohydrologic conditions, which would strongly affect well field design, construction, and operation. On the other hand, the possibility tends to increase with number of wells and the period of time over which the mine is operated

Galloway, et al., (1981) discuss the geochemical implications of both alkaline and acid leach liquors in Texas aquifers. In the case of an alkaline leach-liquor, they conclude that an excursion from an ore zone into a mineral-poor, normally oxidizing zone would be influenced by only few reactions tending to alter its chemical nature over a short time span. The introduction of a high-pH lixiviant into an environment dominated by quartz and aluminum silicates, they believe, would produce the slow formation of silica and aluminum hydroxides, allowing the pH to remain high while the fluid moved along under hydrodynamic impetus. Similarly, they postulate that the oxidant content of the lixiviant would remain high for considerable distances of travel. An excursion passing into a reduced zone outside the ore production zone would have effects similar to those in the production zone, that is, pH would be lowered, the oxidant would be consumed in reactions with reduced metals, and trace metals would be dissolved into the groundwater.

Although acid lixiviants were not in use in Texas, Galloway, et al., also considered the effects of an acid leach-liquor excursion. In that case, they hypothesized that, even if the pH of the liquor were raised to a near-neutral range by reaction with wallrock minerals such as carbonates, the solubility of trace elements would not be immediately affected.

The conclusion that dissolved trace elements will probably not quickly reprecipitate or be adsorbed is supported by the observations of Henry, et al., (1980), who offer evidence that trace elements tend to remain in solution even after Eh conditions have changed from oxidizing to reducing.

Thus, the environmental threat presented by excursions of leach liquor is one that must be controlled by artificial means, as natural controls that would remove the threat in an acceptably short time period appear to be lacking.

Radioactive Materials

The radiological effects of uranium and its decay products constitute a health hazard that is distinct from the hazard due to its toxic properties. These effects are a special concern where excursions of leach liquor threaten potential drinking water supplies and at surface facilities where leach liquor and process wastewater are in contact with humans and the environment.

Most uranium contains more than 99 percent of uranium 238, which evolves through radioactive decay over an extended period of time (4.5 x 10^{9} years) into an isotope of lead, Pb^{206}. Numerous other unstable daughter products are formed during the transition from U^{238} to Pb^{206}, and in many ore deposits all of the daughter isotopes are present in constant proportions. Of these daughter products, radium 226 (Ra^{226}) is considered to present the greatest threat to groundwater resources because of the potential radiation effects of its daughter products. Its immediate daughter, radon 222 (Rn^{222}) is a gas which can be released into the atmosphere.

Excursions of leach liquor transport radioactive materials as well as other dissolved metals. Kasper, et al., (1979), state that the data base covering the long-term effects of such excursions is very small, but that available evidence from cleanup operations suggests that the radioactive materials are returned to the producing zone along with the other contaminants when remedial measures are taken. They also point out that there is a significant difference between the solubility of radium in acid and alkaline lixiviants; in a typical acid leach operation, only 0.38 percent of the total radium 226 in the ore is dissolved, whereas in a typical alkaline leach operation, about 2 percent of the radium in the ore was dissolved. Thus, the potential impact of radioactive contamination by an excursion from an alkaline-leach mine can be expected to be considerably greater than an excursion from an acid-leach mine.

4.3 SURFACE WATER CONTAMINATION

Leach liquors and mill process waters that are not re-injected may contaminate surface waters. The waste streams depicted schematically in Figure 4 all contain non-radioactive potential contaminants in various concentrations that must be handled to avoid contamination of surface waters. These waste streams all contain trace amounts of radioactive material that cannot be released into the environment even in diluted form.

Because disposal of radioactive wastewater is expensive, most plants are designed to recirculate and to reuse process waters. A summary compiled by Kasper, et al., (1979), of annual volumes of wastewaters generated by a hypothetical plant is presented in Table 7. The authors point out that the wastewaters produced during the restoration period is based on a 10-pore volume flushing program to be carried on in one-year-long increments for a total of nine years. Such an estimate may be low, as flushing volumes as high as 25-pore volumes have been required to attain baseline or acceptable restoration in some cases. At the Nine-Mile Lake mine, more than 20 pore volumes (estimated) of flushing were required to achieve near-baseline values for the groundwater in the production zone (Englemann, et al., 1980).

As many of these waste streams are characterized as brines (1500-5000 mg/L TDS), they would have an adverse effect on surface waters if discharged into the environment.

Where liquids are transferred from point to point, either through pipes or in open settling or evaporation pond systems, the possibility of system failure or operator error exists. The accidental escape of hazardous or otherwise undesirable materials into the environment can be minimized by incorporating safety factors or backup features in the design of the facility. However, because there is great variation among in situ mining operations and their associated environments, specific environmental impacts must be evaluated case by case.

4.4 ATMOSPHERIC CONTAMINATION

Atmospheric emissions at an in situ solution mining operation are slight compared to those from conventional surface or underground mining operations, but radioactive emissions pose the most important health concerns.

Radioactive Emissions

Radon gas from the pregnant liquor surge tank and uranium 238 oxide dust from the yellowcake dryer are the primary emissions from an in situ mining operation and its recovery plant (Kasper, et al., 1979). Evaporation ponds are also a potential source of radon. Because of the difference in solubility of radium 226 in acid and alkaline solutions, approximately 0.02 percent of radium in an ore body is precipiated as yellowcake at a typical acid leach operation, as opposed to about 2.0 percent at an alkaline leach operation. Measured values at the Irigarary mine in Wyoming support the conclusion that human populations are characteristically exposed to doses of less than 0.1 percent of the allowable maximum under NRC standards and 5 percent under proposed USEPA standards.

The effect of atmospheric emissions from the Irigaray mine on the populations within an 80.5 km (50 mile) radius was estimated by the NRC to be less than 5 x 10^{-4} percent of the dosage provided by natural background radiation (USNRC, 1978).

Ledbetter (1980) summarized the occurence and effects of radioactive materials in and near uranium mines and concluded that the hazard from radon is practically eliminated at above-ground operations by natural ventilation.

Table 7, Wastewaters Generated by Ion Exchange, 500,000 Pounds Uranium per Year In Situ Solution Leaching Operation Main Lixivant Circuit Flowrate = 63 l/sec (1,000 gpm), 24-hour operation

Waste Stream	Description	Flowrate	Annual Volume
1. Lixiviant Bleed	Barren Lixiviant bleed produce net inflow into mine area.	1.25 l/sec (20 gpm)	2780 m^3 (32 AF)
2. Spent Resin Wash	Water used to wash NH_4 Cl from spent resin.	0.63 l/sec (10 gpm)	1390 m^3 (16 AF)
3. Eluant Bleed (a)	Barren eluant bleed prevents salt accumulation in closed circuit.	0.63 l/sec (10 gpm)	1390 m^3 (16 AF)
4. Well Cleaning	Injection wells must be flushed to prevent clogging (2500 gal/well/month)	0.2 l/sec (3 gpm)	420 m^3 (5 AF)
5. Monitoring Wells	Flushing well prior to sampling produces representative sample 50 monitoring wells @ 250 gallons twice per month.	0.02 l/sec (0.3 gpm)	42 m^3 (0.5 AF)
6. Sanitary Wastes (b)	1.25 l/sec (20 gpd)/employee x 60 employees	0.05 l/sec (0.8 gpm)	110 m^3 (1.3 AF)
7. Restoration	Water flushed through leached areas to remove all traces of lixiviants.	6.4 l/sec (102 gpm)	14,170 m^3 (164 AF)

(a) Lixiviant bleed can be used - flowrate is then contained in Item 1.
(b) Low water use fixtures, assumes showers for 80 percent of employees.

Ref: Kasper, et al., 1979.

effects. He pointed out that uranium itself presents little or no external body hazard. Measures to prevent the inhalation and ingestion of dust are effective in controlling the internal hazard.

Non-radioactive Emissions

Non-radioactive atmospheric emissions that are specific to in situ uranium plants include ammonia, ammonium salts, and carbon dioxide. These materials are emitted at the yellowcake dryer, from the surface of storage and disposal ponds, and at water purification units. Ammonium chloride particulates may be emitted from evaporation ponds; however, the transport of particulates from pond areas is minimized by the maintenance of a supply of liquid in the ponds. All of these are relatively low-level emissions and have minimal or no adverse environmental impact (Kasper, et al., 1979).

4.5 GROUNDWATER CONSUMPTION

Because of restoration requirements, there may be relatively little net removal of water from subsurface aquifers as a result of in situ mining operations. Kasper, et al., (1979) point out that the hypothetical plant described in Table 7 can produce as little as 1.47 L/sec. (23.3 gpm) of radioactive wastewater if maximum in-plant reuse of water is practiced. Restoration water is treated at the surface and re-injected, producing a relatively small waste stream for each pore-volume of flushing water. Kasper, et al., (1979) conclude that consumptive water use would have only local effects and would not adversely affect regional water supplies in either the Texas or the Wyoming type ore-bearing formations. Galloway, et al., (1981), however, conclude that the projected increase of in situ mining in Texas will have an increasing effect on regional hydrology, and recommend detailed pre-operational tests and post-restoration monitoring programs to provide more information on the sensitivity of aquifers there.

As not all mining operations recycle the produced water, consumption of water varies. Net removal may be large in some operations.

SECTION 5

CONTROL TECHNOLOGY

Technologies for the control of pollution from in situ and heap-leach extraction of uranium include many which are common to the mineral processing industry or other industries in general, such as dust and noise control technologies. Several areas, however, are more specific to the solution mining and processing of uranium, and they are discussed in this chapter. These technologies can be grouped into three broad categories: (1) mining operations; (2) cleanup and restoration; and (3) waste disposal.

5.1 MINING OPERATIONS

Water Barriers

To be suitable for in situ leaching, a uranium deposit should be bounded above and below by impermeable strata and be located below the water table (Riding, et al., 1979). Impermeable strata or aquicludes vertically bounding the uranium deposit figuratively function as dams which prevent leach solution from flowing into the overlying or underlying strata. Water flows through these aquicludes but the rate is so slow that vertical migration of the leach solution can be avoided if the aquiclude is isotropic throughout. Aquicludes, however, are not always isotropic in their permeabilities. Anomalies in the permeability of an aquiclude may result from fracturing, lithologic differences, and improperly sealed wells. Potential breach zones of the aquiclude such as fractures and high permeability zones can be sealed by grouts or slurries. Grouts and slurries are discussed later in this report.

Wells that are drilled into the ore bearing strata but improperly sealed are the most vulnerable locations through which migration of the leach solution may occur. It is imperative that the annular space and fractures produced adjacent to the drill hole as a result of the drilling operation can be sealed off. Sealing of the annular space and associated drilling fractures is commonly done with cement. To maintain the integrity of the well, the cement seal and well casing should be stable in the presence of the injected leaching solution. Centralizers used during placement of the cement will help to insure that all of the annular space is sealed off. Cement or cement grout placed under pressure will permeate naturally present fractures and those induced by drilling. The use of cement grouts is limited by the size of the spaces which they are capable of penetrating. It may be necessary to use clay or chemical grouts to seal off small fractures.

Abandoned exploration wells in the vicinity of in situ uranium mines must be adequately plugged in order to prevent the migration of contaminants through them. Most states have adopted regulations governing the abandonment of exploration wells.

In the event of an excursion through a well during the active life of an in situ mine, the location of the break in the well seal can be determined by pressure testing. Pressure testing entails establishing a relatively high pressure within a packer and measuring any loss in pressure. Should pressure drop, it may be inferred that a break exists in the well casing or well seal within the increment being tested.

Control of Water Movement by Pumpage

Current technology used to control the flow of lixiviant in the strata containing the ore body involves establishing subsurface flow systems between the injection and pumping wells by differential pumping. The leach solution injected into the ore body will initially flow out in a radial pattern. Pumping of the production well controls the outward flow of the leach solution by creating a low pressure area to which the injected solution will flow. The resulting flow pattern from the injection well to the production well approximates a tear shape with the large end of the tear at the injection well and the smaller end at the production well.

The distance which the fluid lines extend from the injection well determines the areal extent of the leach solution and is dependent upon the amount of fluid injected and pumped out. The greater the differential between volumes of pumping and injection, the lower the pressure at the production well and the smaller the areal extent of the lixiviant. In the event of an excursion, the differential pumping scenario described above creates an increased hydrodynamic gradient which tends to draw the excursion toward the pumping well.

Another method of controlling lixiviant migration is the establishment of a pumping trough. In the event of an excursion, wells surrounding the ore body are pumped. The pumping wells then form a trough in the piezometric surface into which the leach solution flows. The hydrodynamic gradient thus created initially limits leachate excursion. Eventually, the contaminants will be removed, as the aquifer is flushed by inflowing groundwater. However, such a method reduces the usable storage capacity of the aquifer and utilizes large volumes of native groundwater.

A pressure ridge, or water barrier, can also be used to control excursions. This method involves the use of a line of recharge wells that pump water into the formation to form a ridge in the piezometric surface. The pressure ridge must be initiated outside the lixiviant-fresh water front in order to prevent driving the excursion further away from the leach zone. Lixiviant will not transgress the pressure ridge if the ridge is of significant pressure and a pumping well is used to provide a low pressure zone into which the lixiviant can flow. The ridge produced by the recharge wells would consist of a series of peaks at each well with saddles in between. The necessary elevation of the saddles to displace the lixiviant would govern the well spacing and the recharge rates required. This method of control does not restrict usable groundwater storage capacity but has the disadvantage of requiring supplemental water.

Grouts

Migration of the lixiviant in the vertical and horizontal planes can be restricted by decreasing the natural permeability via grouting.

While the use of grouting techniques in the in situ mining industry appears to be rare, the method has potential application in isolating difficult to restore zones from regional circulation and in controlling leakage through aquicludes. Grouting is usually relatively expensive, and may be economical only in certain situations.

Common grouting procedures involve drilling through casing anchored sufficiently to withstand the applied pressure. The permeability of the strata is tested, grout is chosen in accordance with the conditions and objectives of the grouting program and then it is injected. Deep holes are commonly grouted in stages; for example, the hole is drilled until a permeable zone is found and then grout is injected. After the grout has set, the hole is drilled out, deepened, and grouted again (Int. Soc. Soil Mech. and Found. Engnrg., 1963).

In order to permeate the rock, the grout pressure should exceed the hydrostatic pressure but not the vertical stress (Cummins and Given, 1973). Injecting grout at pressures greater than the vertical stress can open additional fractures in the rock.

There are basically three types of grout: cement, clay, and chemical. Of these, only the first two are considered here, because the polymerizing compounds used in chemical grouting may contaminate the area. The objectives of a grouting program and the funds available for it control the choice of grouts to be used.

Cement Grout--

Cement grout is commonly used to fill moderate or large voids in component rock. Cement slurries enter fractures and pores larger than 1 millimeter at the rate of about 0.3 cm/sec in coarse sand. Penetration can be improved with sodium silicate or clay lubricant, but even with these admixtures medium porosity sands are the penetration limit (Cummins and Given, 1973).

Bentonite will improve the pumpability of cement slurries and prevent the separation of water in the grout mixtures; however, it decreases the strength of the grout (Int. Soc. Soil Mech. and Found. Engnrg., 1963). Clay-cement grouts will bond with native clays, unlike neat cement and cement-sand grouts. The setting times of clay-cement grouts are slow and inexactly known.

The water-cement ratio is important in controlling the behavior of cement slurries. When a large number of small openings are to be plugged, a relatively thin slurry with a ratio of five parts water to one of cement is commonly used. If a large quantity of grout is accepted without a pressure increase, it is probably running through a conduit in the material which is to be grouted. Remedies include decreasing the water-to-cement ratio, adding bridging material such as gravel, reducing the rate of pumping, and letting the hole stand for several hours (Cummins and Given, 1973).

Clay Grout--

Clay grout is commonly used to fill small void spaces in weak ground to resist low pressure gradients. The advantage of colloidal suspensions with clay is that they can fill voids as small as 0.1 millimeters at a rate of .001 cm/sec in medium sand. Clay grouts will bond with native clay, unlike neat-cement and cement-sand grout. However, setting time is indefinite and some clays are thixotrophic, that is, they may become fluid when disturbed (Cummins and Given, 1973).

5.2 CLEANUP AND RESTORATION

Ion Exchange

Ion exchange is a hydrometallurgical concentration method based on the selective adsorption of metal-bearing ions onto ion exchange resins. The resins consist of an elastic, three-dimensional network of hydrocarbon molecules which carry fixed charges. They are formed into spherical "beads," which range in diameter from 0.5 to 2 mm.

There are two basic types of resins: 1) cationic resins, which exchange cations; and 2) anionic resins, which exchange anions. Anionic resins are used for the recovery of uranium. A typical anionic exhange mechanism is shown in the following reaction:

$$\underset{\text{Resin}}{2\ R - Cl^-} + \underset{\text{Uranyl dicarbonate}}{UO_2\ (CO_3)_2^{--}} = R_2 - UO_2\ (CO_3)_2^{--} + 2Cl^-$$

The resin carrying the chlorine anion is reacted with uranyl dicarbonate (or tricarbonate, depending on solution pH), causing the complexed uranium to adsorb onto the resin while the chlorine ion goes into solution. The selectivity of the resin for metal ions is a prime factor in resin selection. Generally, however, ions having high charges that are opposite to the charge of the resin are favored for adsorption; for ions of the same charge, those with the smaller solvated volumes are favored. The problem of co-adsorption of metal ions is lessened in the uranium exchange procedure because few metal ions form anonic complexes. A partial list of resins commonly used for uranium recovery is shown in Table 8. The theoretical capacity of all these resins is approximately the same; however, actual tests have shown variations from 77 to 385 KG of U_3O_8 per cubic meter of resin. The wide variation in loading is due to differences in lixiviant concentration, grade of pregnant liquor, pH, and purity of the feed solution.

Table 8. Ion Exchange Resins Employed by the In Situ Uranium Mining Industry

Resin	Manufacturer
Amberlite IRA 430	Rohm & Haas Company
Dow X 21K	Dow Chemical Company
Duolite A-101D	Diamond Alkali Company
Ionac A-580	Ionac Chemical Company
Permutit S-700	Permutit Research and Development Center

Figure 5 is a schematic illustration of an ion exchange column. The pregnant leach solutions from the well field pass into the ion exchange column and percolate through the resin column. The barren lixiviant passes out the bottom of the ion exchange column. It is then chemically refortified to restore reagent lost to the host formation through chemical and/or sorption reactions and is reinjected into the formation. Some provision must also be incorporated in alkaline leach circuits for calcium control, since alkaline leach solutions are usually supersaturated with respect to calcium carbonate. Such provision may be either upstream or downstream from the ion exchange process.

When available ion exchange sites are filled, the ion exchange column is either taken off stream (fixed bed) or the most heavily loaded beads are extracted and fresh ones added (fluidized bed). In the former case, the process stream is diverted to another ion exchange column while the loaded beads are eluted. In the latter, countercurrent circulation is employed. When the beads are loaded, the current direction is reversed and the most heavily loaded beads, i.e., the oldest, are flushed from the column while fresh beads are loaded at the other end. The fixed bed is most commonly employed since it requires a less sophisticated mill circuit. The fluidized bed, however, has certain advantages in that only the most heavily loaded resins go to the elution stage, and column down time is reduced.

To remove the adsorbed uranium from the ion exchange beads, the original process is reversed during an elution stage based on the following reaction:

$$R_2 - UO_2\,(CO_3)_2^{--} + 2Cl^{-} = 2R\text{-}Cl + UO_2\,(CO_3)_2^{--}$$

The elution process strips uranium from the resin and concentrates it in solution. The uranium concentration of the pregnant eluant is approximately 40 to 60 times greater than that of the pregnant lixiviant.

In general, most plants use a chloride based salt (NaCl or NH_4Cl) to regenerate the loaded resin. However, although chloride is an effective eluant, a small amount will be transferred to the barren liquor and eventually will be recycled to the injection wells. This buildup in chloride content will eventually impair the loading capacity of the resin. For this reason some plants are switching to ammonium carbonate-ammonium bicarbonate. While not as effective as chloride, these do not cause extraneous ions to be introduced to the aquifer.

The stripped beads are returned to the process stream for reloading. In the fixed bed concept, the column merely goes back on stream, while in the fluidized bed concept, the beads are returned to the column as fresh beads.

The pregnant eluate goes to precipitation tanks where the uranium is recovered as UO_2. Various systems are used. Conventional resin elution with NaCl solution is followed by a caustic precipitation. For circuits using NH_4Cl, the pregnant liquor is acidified with HCl prior to precipitation with NH_3.

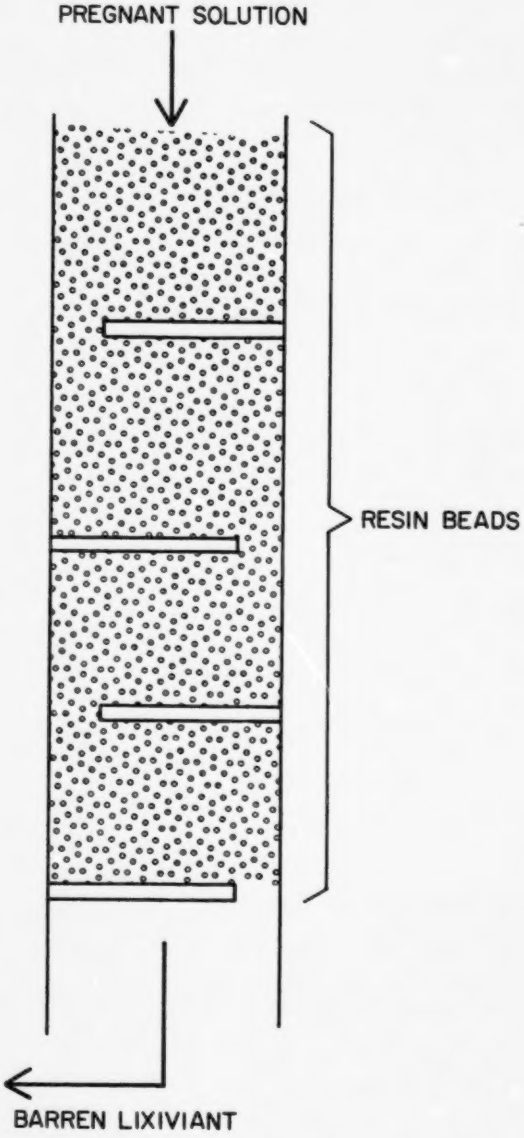

PREGNANT SOLUTION
RESIN BEADS
BARREN LIXIVIANT

Figure 5. Ion Exchange Column

Reverse Osmosis

Osmosis is a process in which two solutions of different concentrations are separated from the same solvent by means of a permeable membrane. If the membrane is permeable to the solvent and not the solute, then the solvent will flow from the dilute to the concentrated solutions until equilibrium is established. In reverse osmosis, the procedure is reversed by application of pressure to the more concentrated solution. Thus, it becomes possible to separate dissolved solids from water, resulting in clarified water and a concentrated brine solution.

Commercially available systems force water through a semi-permeable membrane at pressure of 410 to 4,100 kPa (60 to 600 psi). Two types of membrane configurations are available--spiral wound and hollow fine-fiber. Spiral wound modules have better-defined flow channels than the hollow fiber modules and therefore are more readily cleaned if fouled or scaled. The spiral wound modules also have a lower feedwater pretreatment requirement.

Newly developed systems are highly selective and will reject most metals. Field demonstrations have shown that for every four liters of influent, three liters of purified water are obtained and 99% of the dissolved metals are removed. More recent studies of the in situ uranium industry (Kasper, et al., 1979) have indicated that on the average, every five liters of influent water yields four liters of purified water that exceeds potable quality.

Despite its widespread adoption by the uranium industry, reverse osmosis is not without significant problems. It has proven too costly for adoption by other industries, coal mining, for example, and for the smaller in situ operation, it may not be economically practical. Furthermore, waste solutions require pretreatment, and this can be complex, depending on the nature of the waste solutions. At minimum, influent solutions with significantly high concentrations of iron, that is, those operations employing acid lixiviant, must also maintain pH values below 3.0 to prevent iron precipitation on the membrane. Perhaps the greatest problem may be the high concentrations of calcium sulfate or calcium carbonate in influent water. Further concentration of this dissolved constituents by the reverse osmosis process results in precipitation of the calcium sulfate or calcium carbonate on the membrane. Pretreatment processes, such as calcium removal by ion exchange or lime softening can precipitate the calcium and thus reduce membrane fouling.

Disposal of the resultant brine continues to remain a problem. The size of evaporation ponds can be reduced significantly but, in areas where net evaporation does not exceed precipitation, deep well injection is still necessary and the processed, concentrated solutions may be even more environmentally objectionable. The decrease in volume of the injected solution does, however, decrease disposal costs. Deep-well injection as a method of waste disposal is discusssed in Section 5.3.

Pretreatment of Ore-Bearing Aquifers

In order to facilitate the in situ mining process, ore-bearing aquifers may be treated using a variety of techniques. Usually, these treatments are aimed at improving the permeability or flow characteristics of the formation. This may consist simply of producing and re-injecting native groundwater; this establishes flow gradients and often flushes out intergranular fines. Pressurization by air has also been used to "clean" the aquifer prior to injection of lixiviants at some operations.

Recent work indicates that chemical pretreatment of the formation may also reduce the formation of calcium carbonate in the low-pressure zones around production wells. Where potassium carbonate-bicarbonate lixiviants are used, this treatment also has the advantage of drastically lowering the rate of consumption of the solvent (Tweeton, et al., 1980). This study tested the advantages of using potassium chloride as a pre-flush solution.

Permeability loss occurs near the production well screen when $CaCO_3$, which is supersaturated in the lixiviant, precipitates out. Preflushing with KCl removes calcium from the orebody prior to leaching with a carbonate lixiviant. $CaCl_2$ is more soluble than $CaCO_3$ and will not precipitate as readily when entering the area of reduced pressure near the well screen, thus reducing the scaling problem.

Test results indicated that permeability loss was reduced with a chloride preflush before leaching with either NH_4Cl or K_2CO_3. The reduction in permeability loss was found to be most effective where the loss without the preflush would be greatest.

Uranium recovery percentages were not reduced by the chloride preflush. In one test using the ammonium carbonate lixiviant with the NH_4Cl preflush, the recovery percentage increased. The high cost of NH_4Cl, however, effectively prohibits its commercial use at this time.

This study also tested the feasibility of using potassium carbonate as a lixiviant. Potassium carbonate is much more expensive than ammonium carbonate ($27.60/lb-mole vs. $4.08/lb-mole); this cost can be reduced by flushing the leach zone with much cheaper potassium chloride prior to solution mining. Potassium chloride satisfies cation exchange sites in the leach zone, thereby reducing consumption of the more expensive potassium carbonate by 83%. The advantage of using K_2CO_3 as a lixiviant is that the baseline potassium concentration is normally high for groundwater and is not considered harmful. Restoration parameter levels are therefore easier to achieve.

Should permitting regulations require it, however, it may be necessary to inject a solution of high ionic strength to remove the potassium ions adsorbed on the clays in the formation. This depends on the stringency of the restoration parameters regarding potassium. The calcium from the solution produced during the chloride preflush would be an ideal cation for exchange with potassium, as it is already in the ore-bearing formation and would not lead to further restoration problems.

Removal of Ammonium Ions After Leaching

Uranium deposits that occur in calcareous sandstones have presented special problems to in situ leach operations. Acidic lixiviants cause dissolution of carbonate minerals, which subsequently precipitate during processing, thereby fouling equipment. To avoid this problem, alkaline lixiviants are widely used. Ammonium carbonate and bicarbonate solutions have become the preferred solvents in lixiviants. The use of alkaline lixiviants, however, is not without problems.

Most uranium orebodies contain up to 20% clay. The clay acts as an ion exchange medium for the leach solution, according to the following equations:

$$\text{Na Clay} + NH_4^+ = NH_4 \text{ Clay} + Na^+$$

$$\text{Ca Clay} + 2NH_4^+ = (NH_4)_2 \text{ Clay} + Ca^{++}$$

The selectivity of clays for NH_4^+ is high and the overall post-leaching concentrations of NH_4 in the formation can become quite high (in excess of 2000 ppm). If not removed during restoration, the NH_4^+ ions will be released slowly by exchange with incoming cations in the groundwater, resulting in pollution of the aquifer.

Post-restoration concentrations of ammonium on the order of 0.01 to 10 ppm are required if regulations are to be met. Computer models indicate that such a restoration could take decades if simple flushing alone is employed. In fact, field restoration tests have shown that it is extremely difficult to reduce NH_4^+ concentrations to less than 100 ppm even after flushing with 6 to 10 pore volumes of water.

Mobil Oil Corporation (Yan, 1980) has developed the following three-step process which an result in a more rapid reduction of the ammonia concentrations:

1) The leached formation is flushed with connate water to remove the initial easily soluble ammonia

2) Chlorinated water or hypochloric solution is injected at a pH of 8 to 10

3) The formation is flushed to lower the Total Dissolved Solids to the desired level.

The overal reaction between NH_3 and chlorine can be summarized as follows:

$$2NH_3 + 3Cl_2 \quad 6H^+ + 6\ Cl^- + N_2(\text{gas})$$

The normal decompositon reaction is quite rapid, producing nitrogen gas and chloride ion. The overall reaction is irreversible, making the complete removal of the ammonium ion possible; because the nitrogen is removed as a gas, the volume of water to be disposed of is reduced.

Controlled laboratory experiments have shown that flushing with less than three volumes of pore water have effectively reduced ammonia concentrations to less than 3 ppm. The only drawback to the method is the large volume of Cl_2 necesary to treat the NH_3 (6 pounds Cl_2 per 1 pound NH_3). Commercial application of this process has not been reported, and it remains to be seen if ammonia concentrations can be reduced to less than 1 ppm with this method.

5.3 DISPOSAL OF WASTES THROUGH INJECTION WELLS

Deep-well injection has become a widely-used procedure for the disposal of liquid wastes. From 1964 to 1973, the number of waste injection wells (excluding oil-field brine wells) increased from 30 to more than 280 in 24 states. The injection of brines separated from crude oil production wells is a common practice in the petroleum industry; over 100,000 of these wells existed in North America in 1979 (Freeze and Cherry, 1979, p. 454).

The diposal of liquid waste by injection involves essentially the same mechanical and hydrogeological principles as does the withdrawal of subsurface fluids. As in the latter case, formation permeability characteristics strongly influence the volumes and flow rates of fluids that can be accepted by a given aquifer, while fluid and chemical characteristics of the injected liquid may affect equally strongly the behavior of the waste as it moves through the formation.

Most injection wells are completed in formations 300 to 2100 m (1000 to 7000 feet) beneath the surface. For obvious reasons, disposal aquifers must be selected only from among those which have no potential for use as suppliers of water to the surface. It is equally important that no hydraulic connections exist between aquifers used for waste disposal and aquifers which contain potentially usable groundwater.

In practice, waste liquid is injected under pressure into the formation. A pressure mound results. The size and shape of this mound varies with rate and pressure of injection and the ambient flow characteristics of the groundwater already in the formation; generally, however, as injection continues, the presure mound spreads over a widening area. The spread of the injected waste itself increases at a slower rate as the formation water is displaced before the advancing front (Freeze and Cherry, 1979).

The volume of wastewater to be handled is of primary importance on that it limits the feasibility of using subsurface injection in many instances. In areas of favorable geology such as the Texas Gulf Coast rates of injection through a single well can be as high as several hundred gallons per minute on a sustained basis. In contrast, in the interior geologic basis of Wyoming and New Mexico injection rates are more commonly limited to tens of gallons per minute. This difference in injection reservoir capability is one of the reasons why injection wells have been frequently used in conjunction with uranium leaching operations in the Texas Gulf Coast region, whereas impoundment and evaporation has been the principal disposal method selected for operations in the Rocky Mountain states.

Systems for injection of low level liquid radioactive wastes are carefully designed and constructed to minimize the potential for contamination of useable groundwater. Figure 6 diagrammatically shows the design features that are routinely incorporated in such injection wells. The actual de-

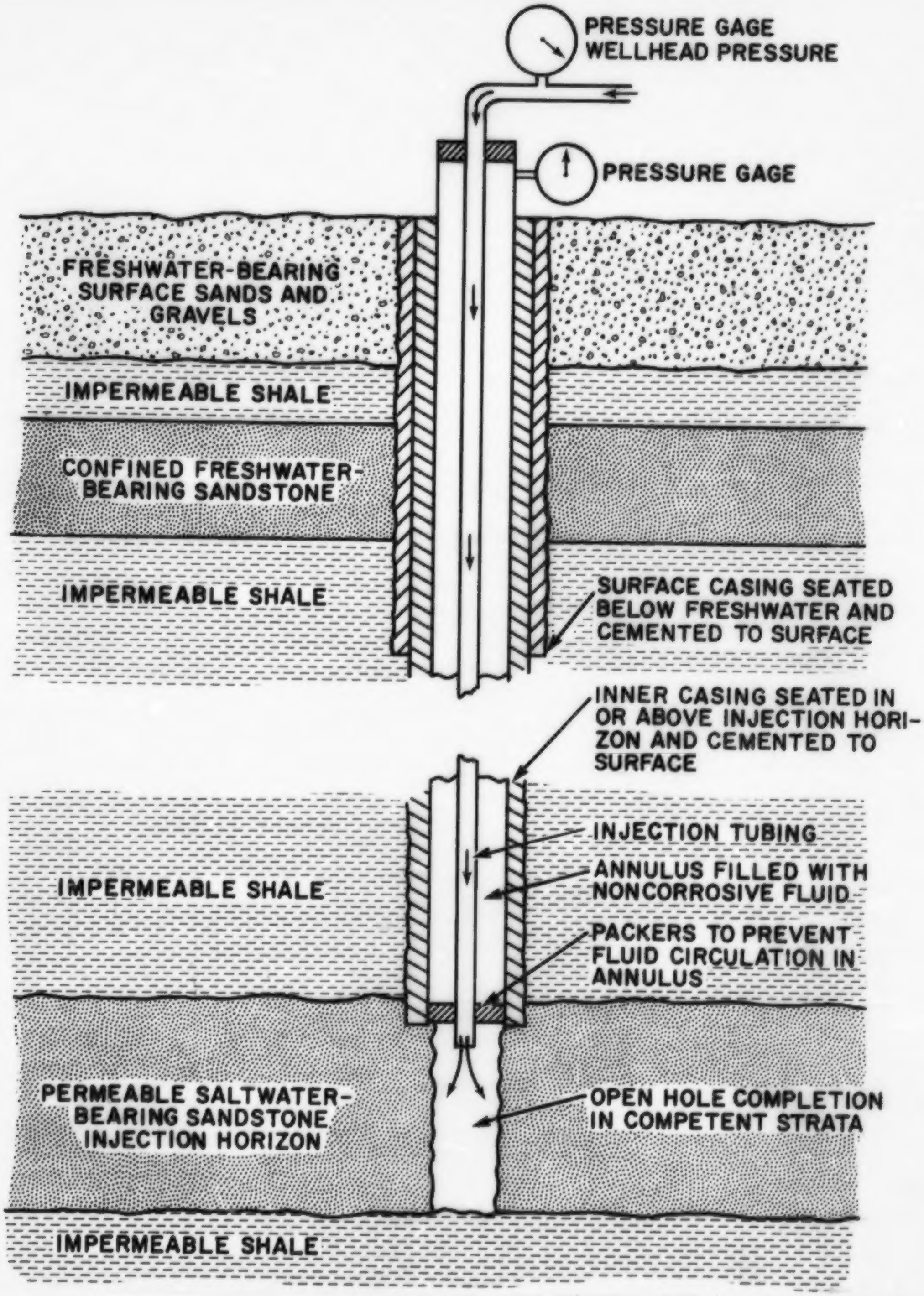

PRESSURE GAGE
WELLHEAD PRESSURE
PRESSURE GAGE
FRESHWATER-BEARING SURFACE SANDS AND GRAVELS
IMPERMEABLE SHALE
CONFINED FRESHWATER-BEARING SANDSTONE
IMPERMEABLE SHALE
SURFACE CASING SEATED BELOW FRESHWATER AND CEMENTED TO SURFACE
INNER CASING SEATED IN OR ABOVE INJECTION HORIZON AND CEMENTED TO SURFACE
INJECTION TUBING
IMPERMEABLE SHALE
ANNULUS FILLED WITH NONCORROSIVE FLUID
PACKERS TO PREVENT FLUID CIRCULATION IN ANNULUS
PERMEABLE SALTWATER-BEARING SANDSTONE INJECTION HORIZON
OPEN HOLE COMPLETION IN COMPETENT STRATA
IMPERMEABLE SHALE

Figure 6. Industrial Waste Injection Well Completed in Competent Sandstone (after Warner, 1965)

sign of a particular well is dictated by the site geology and wastewater volume and chemistry.

In addition to technical and economic factors, Federal and State regulations must be considered when the use of injection wells is contemplated (Appendix B). In particular, the recent promulgated Underground Injection Control Regulations (U.S. EPA, 1980) dictate many aspects of injection well design, construction, testing and operation.

The local geologic and hydrologic conditions necessary for successful and safe subsurface injection are shown in diagram form in Figure 7. Very briefly, a potential disposal site and injection interval should have the following characteristics (Warner and Lehr, 1977):

a. Injection interval should be sufficiently thick, with adequate porosity and permeability to accept waste at the proposed injection rate without necessitating excessive injection pressures.

b. Injection interval should be of large enough areal extent so that injection pressure is minimized and so that injected waste will not reach discharge areas.

c. Injection interval should be "homogeneous" (without high-permeability lenses or streaks), to prevent extensive fingering of the waste-vs-formation water contact, which would make adequate modeling and monitoring of waste movement extremely difficult or impossible.

d. Overlying and underlying strata (confining bed) should be sufficiently thick and impermeable, to confine waste to the injection interval.

e. Structural geologic conditions should be simple, that is, the site should be reasonably free of complex faulting and folding.

f. Site should be an area of low seismic activity so that the hazard of earthquake damage or triggering of seismic events is minimal.

g. Lateral movement of fluid in the injection interval should be slow under natural conditions.

h. Formation-fluid pressure should be normal or low, so that excessive fluid pressure is not needed for injection.

i. Formation temperature should be normal or low, so that the rates of undersirable reactions are minimized, including corrosion.

j. Wastewater should be compatible with formation fluids and minerals or capable of being made compatible by treatment, emplacement of buffer zone, or other means.

k. Formation water in the disposal formation should be of no apparent economic value, that is not potable, unfit for industrial or agricultural use, and not containing minerals in economically recoverable quantities.

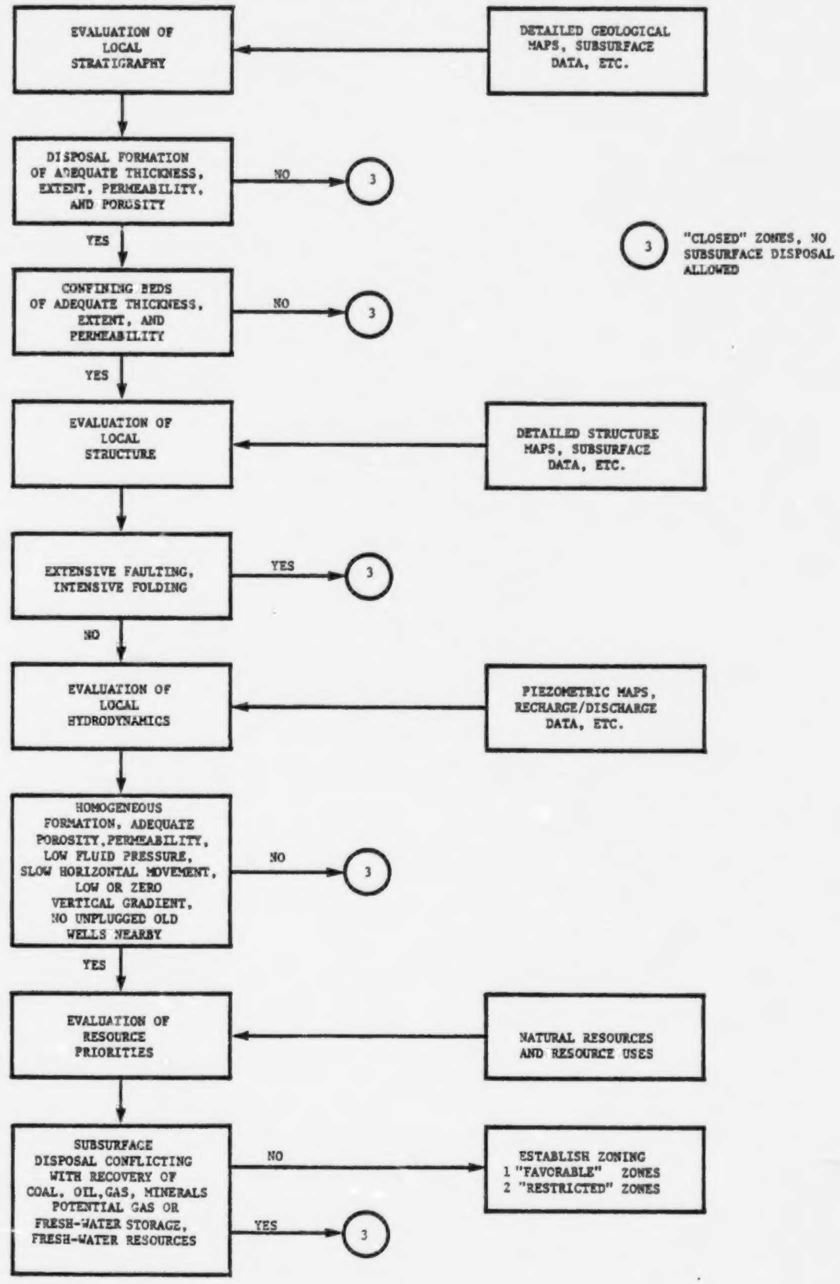

EVALUATION OF LOCAL STRATIGRAPHY
DETAILED GEOLOGICAL MAPS, SUBSURFACE DATA, ETC.
DISPOSAL FORMATION OF ADEQUATE THICKNESS, EXTENT, PERMEABILITY, AND POROSITY
NO
3
YES
"CLOSED" ZONES, NO SUBSURFACE DISPOSAL ALLOWED
CONFINING BEDS OF ADEQUATE THICKNESS, EXTENT, AND PERMEABILITY
EVALUATION OF LOCAL STRUCTURE
DETAILED STRUCTURE MAPS, SUBSURFACE DATA, ETC.
EXTENSIVE FAULTING, INTENSIVE FOLDING
EVALUATION OF LOCAL HYDRODYNAMICS
PIEZOMETRIC MAPS, RECHARGE/DISCHARGE DATA, ETC.
HOMOGENEOUS FORMATION, ADEQUATE POROSITY, PERMEABILITY, LOW FLUID PRESSURE, SLOW HORIZONTAL MOVEMENT, LOW OR ZERO VERTICAL GRADIENT, NO UNPLUGGED OLD WELLS NEARBY
EVALUATION OF RESOURCE PRIORITIES
NATURAL RESOURCES AND RESOURCE USES
SUBSURFACE DISPOSAL CONFLICTING WITH RECOVERY OF COAL, OIL, GAS, MINERALS POTENTIAL GAS OR FRESH-WATER STORAGE, FRESH-WATER RESOURCES
ESTABLISH ZONING
1 "FAVORABLE" ZONES
2 "RESTRICTED" ZONES

Figure 7. Selection of Formations and Areas for Waste Injection (Van Everdingen and Freeze, 1971)

l. Injection interval should be adequately separated from potable water zones, both horizontally and vertically.

m. Waste injection should not endanger present or future use of mineral resources (coal, oil, gas, brine, others).

n. Waste injection should not affect existing or planned gas-storage or freshwater-storage projects.

o. No unplugged or improperly abandoned wells should penetrate the disposal formation because other resources in the vicinity of the disposal site could be contaminated.

At the same time that the geologic and hydrologic conditions are being evaluated, the suitability of the wastewater for injection must be determined. Table 9, lists the factors to be considered in determining the injectability of a wastewater.

A major hazard associated with the practice of wastewater injection in many areas is the presence of abandoned, unplugged wells, which may provide vertical conduits for inter-aquifer migration of contaminants. There may be as many as 1 million unplugged wells in North America, the locations of which are unknown (Freeze and Cherry, 1979).

As has been demonstrated in the solution-mining of uranium, the excursion of injected liquid through mechanical faults in well casing is a serious

Table 9. Factors to be Considered in Evaluating the Suitability of Untreated Wastes for Deep-Well Disposal

---

A. Volume

B. Physical Characteristics

    1. Density
    2. Viscosity
    3. Temperature
    4. Suspended solids content
    5. Gas content

C. Chemical Characteristics

    1. Dissolved constituents
    2. pH
    3. Chemical stability
    4. Reactivity

        a. With system components
        b. With formation waters
        c. With formation minerals

    5. Toxicity

D. Biological Characteristics

---

potential threat to usable groundwater supplies. Careful work and the use of durable materials in well completions may overcome this potential threat on a practical level; however, continued and careful inspections and monitoring are necessary to ensure the continued integrity of injection wells.

SECTION 6

IN SITU MINING OPERATIONS AND THEIR EFFECTS ON WATER QUALITY

In this chapter, partial case histories of operating solution mines are presented, in order to provide practical information on the effects of mining operations on ground and surface water. Information included here was obtained from the public record (i.e., NRC Dockets) and from interviews with representatives of mine operators and regulatory agencies.

6.1 THE CROWNPOINT MINE , MCKINLEY COUNTY, NEW MEXICO

Introduction

Crownpoint Mobil Energy Minerals Division (Nufuels Corp.) operates an in situ uranium leaching project in McKinley County, New Mexico. This pilot test site is located 8 km (5 miles) northwest of the town of Crownpoint, on land leased from the Navajo Indian Reservation (Figure 8). It is on the Chaco Slope, north of the northwesterly trending Zuni uplift along the southwestern flank of the San Juan Basin of the Colorado Plateau. The terrain is characterized by broad expanses of open range land, bounded by cuesta ridges such as Mesa de los Lobos, 8 km (5 miles) south of the project site . Elevation at the site is approximately 2,000 m (6,700 ft). The east-west-trending escarpment of Mesa de los Lobos rises to 2,400 m (8,000 ft). and is the northern edge of the Continental Divide in this region.

In the region, surface waters are limited to intermittent streams with broad valleys, heading in incised arroyos against the mesas. Flow is northerly to the San Juan. Vegetation consists of grassland and scrub trees. The climate of the San Juan Basin is semi-arid, with an average rainfall of 26 cm (10.22 inches). Most of the precipitation occurs in late summer as thunderstorms, and there is no base flow in the numerous stream channels of the project area. All channels flow northerly from the high mesa south of Crownpoint and eventually join Indian Creek, an intermittent stream which is a tributary of the Chaco River. The Chaco River, also an intermittent stream, flows northwest 72 km (45 miles) to the San Juan River, a tributary of the Colorado River.

Stream gradients in the arroyos along Mesa de los Lobos are initially high, as the escarpment drops approximately 390 m there, but level out in the gently rolling basin lands of the project area. Most precipitation either infiltrates or evaporates before it reaches the larger stream beds to the north. The possibility of flooding in the area is very slight and would not affect the pilot site.

The Pilot Plant

Mobil's Section 9 pilot in situ leaching operation occupies 2 ha (5 acres) of an allotted lease of 65 ha (160 acres), which was obtained in 1972. It consists of the wellfield, processing facilities, an evaporation pond, and access roads to all wells (Figure 9). The well field dimensions are 61 m (200 feet) by 61 m (200 feet). The wells are arranged as four 5-spot patterns. The corner wells of each 5-spot pattern are used as injector wells. All wells

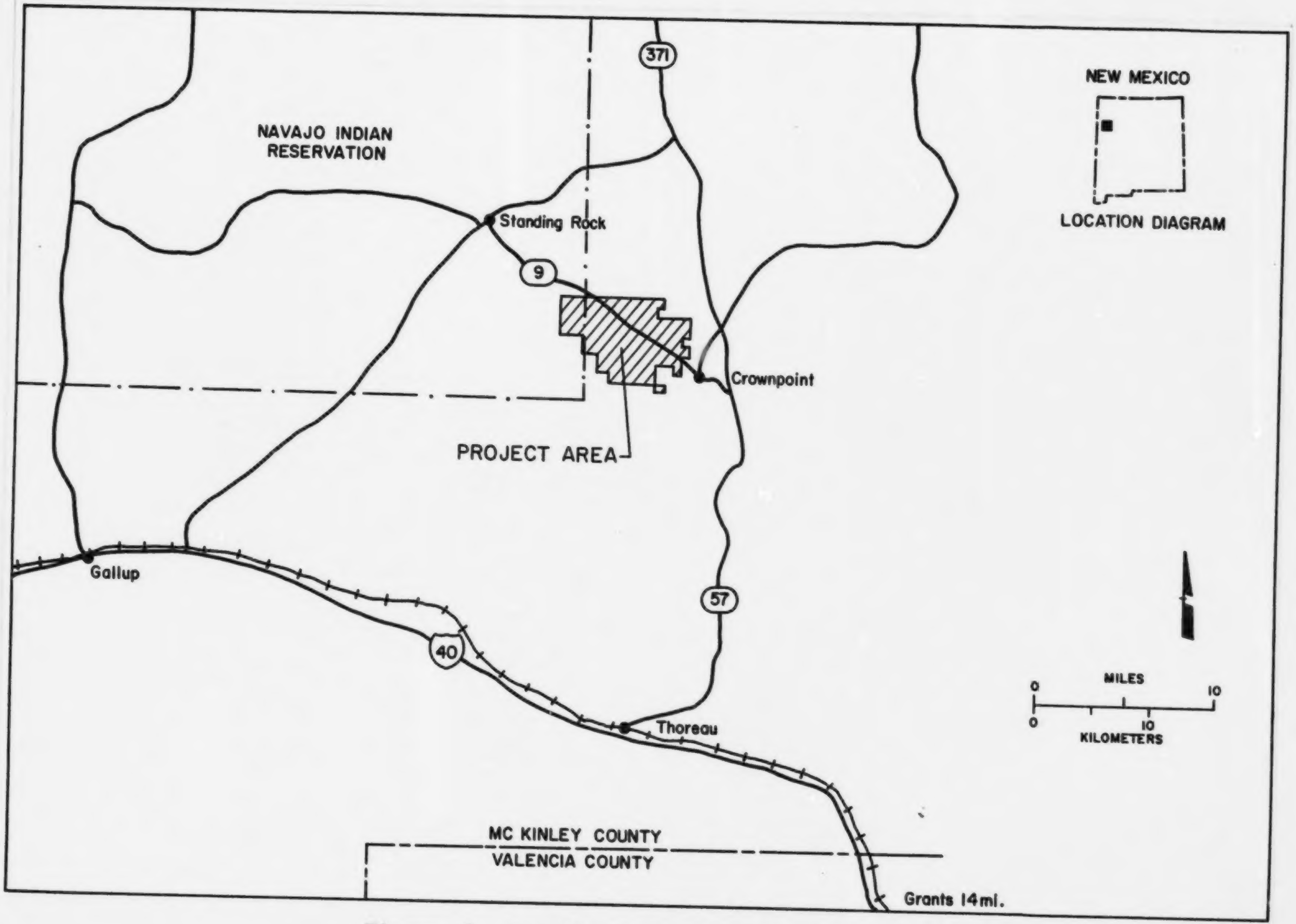

NAVAJO INDIAN RESERVATION
371
Standing Rock
9
Crownpoint
PROJECT AREA
57
Gallup
40
Thoreau
MC KINLEY COUNTY
VALENCIA COUNTY
Grants 14 mi.
NEW MEXICO
LOCATION DIAGRAM
MILES
0
10
0
10
KILOMETERS

Figure 8. Location Map, Crownpoint Mine

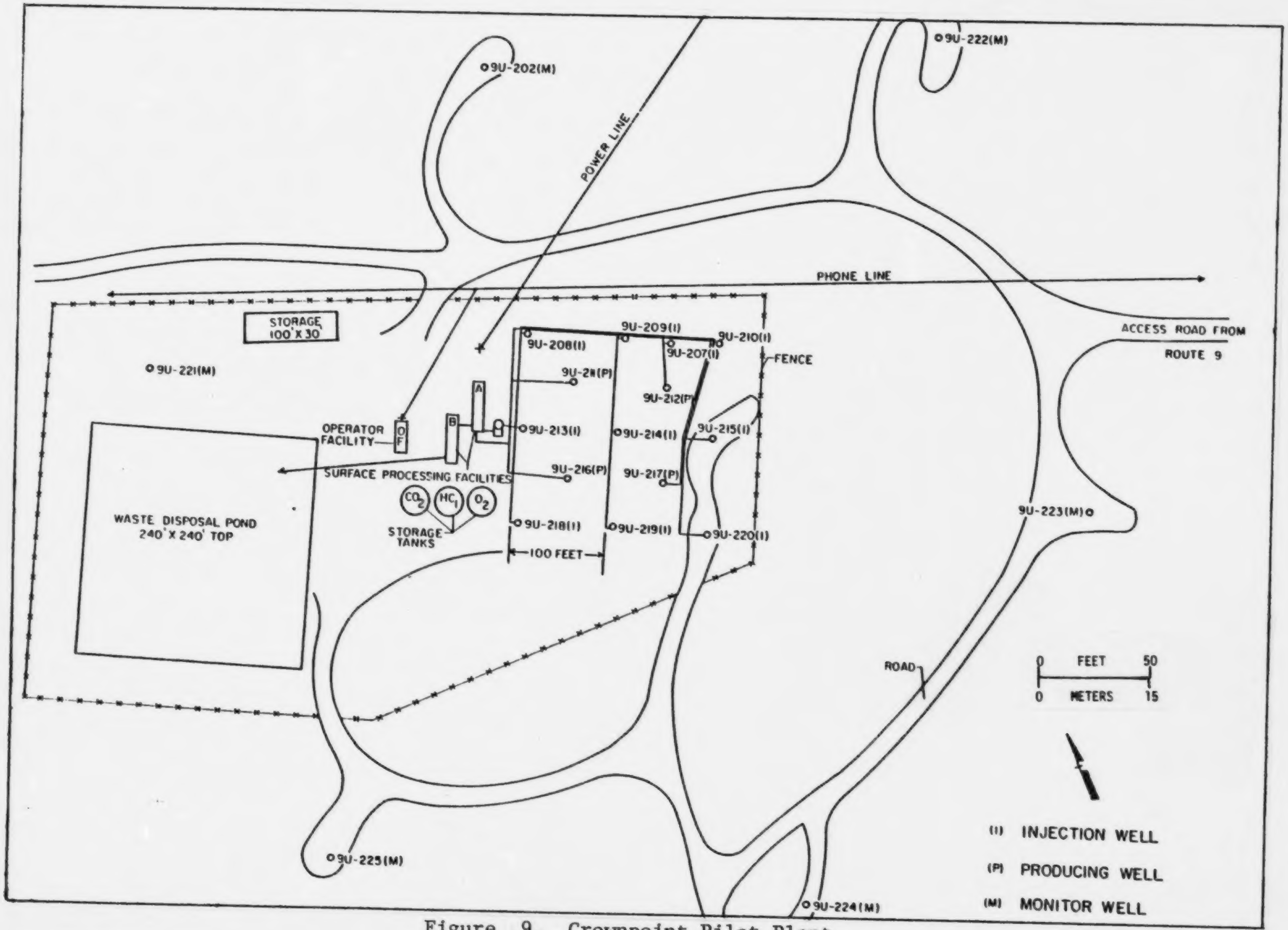

9U-202(M)
9U-222(M)
POWER LINE
PHONE LINE
ACCESS ROAD FROM
ROUTE 9
STORAGE
100'X30'
9U-221(M)
9U-208(I)
9U-209(I)
9U-210(I)
9U-207(I)
FENCE
9U-211(P)
9U-212(P)
A
B
O
F
OPERATOR FACILITY
9U-213(I)
9U-214(I)
9U-215(I)
SURFACE PROCESSING FACILITIES
9U-216(P)
9U-217(P)
WASTE DISPOSAL POND
240'X240' TOP
CO_2
HC_1
O_2
STORAGE TANKS
9U-218(I)
9U-219(I)
9U-220(I)
100 FEET
9U-223(M)
ROAD
0 FEET 50
0 METERS 15
(I) INJECTION WELL
(P) PRODUCING WELL
(M) MONITOR WELL
9U-225(M)
9U-224(M)

Figure 9. Crownpoint Pilot Plant

are capable of either injection or production to facilitate complete ore zone leaching in a commercial operation. Well spacing is 30 m (100 feet) between corners.

The lixiviant is composed of a sodium carbonate-bicarbonate solvent and hydrogen peroxide. The ore zone is in the Westwater Formation, approximately 610 m (2,000 feet) beneath the surface. The uranium occurs as coffinite, in a carbanoceous matrix, with quartz and feldspar.

Six monitor wells surround the production field. The New Mexico Environmental Improvement Division (NMEID) required that the wells be place in a circular pattern with a 120 m (400 ft) radius from the center production well with no more than a 60° arc between the monitor wells. One well (9u 201) was set only 91 m (300 ft) away from the center well because of a property boundary. In addition, NMEID requested that 3 more wells be placed to the northeast, in the direction of groundwater movement. The central well in this direction is perforated in the Dakota sandstone and the Westwater Canyon aquifers. Monitor well 9u 207 is in the northeast corner of the production pattern and was completed in the Dakota Formation to detect any vertical excursions. All the other monitoring wells were completed in the Westwater Formation to detect any horizontal excursions that might occur in the ore-bearing unit.

Hydrogen peroxide was used as an oxidizer in this plant. The depth of the ore body (610 m or 2,000 feet) made it difficult to use oxygen, which costs less, but which must be dispersed as a gas in the liquid lixiviant. Mobil now has the technology to deliver the oxygen at the necessary pressure to this depth, and plans to utilize oxygen in subsequent operations in the Crownpoint area. The H_2O_2 and the Na_2CO_3 are mixed at the surface injection line.

Oxygen transforms the quadravalent uranium to an oxidized hexavalent state, and the bicarbonate ion combines to form a soluble uranyl tri-carbonate complex. The pregnant lixiviant is pumped to the surface, fed through a sand trap to remove entrained sediments, and pumped into storage tanks for loading into the ion exchange column.

The concentration of uranium in the pregnant lixiviant ranges from 50 to 250 ppm. The leach rate is typically adjusted to 6.3 L/s (100 gpm) in this operation. High concentrations of molybdenum occur in this ore body, and this metal is oxidized and solubilized along with the uranium.

The wells were drilled to total depth with a 20 cm (7-7/8 inch) drill bit and cased with 13.97 cm (5-1/2 inch) steel, internally plastic-coated, casing to the top of the Westwater formation. A 13.97 cm (5-1/2 inch) fiberglass casing was set from the top of the Westwater to the bottom of the drill hole. Use of fiberglass casing in the lower part of the well will prevent corrosion caused by the oxidant in the injection stream. Hydrogen peroxide, the oxidant, is injected with the solvent. The well design shown in Figure 10 will be used when gaseous oxygen is the oxidant (it will be injected through a 1.59 cm (5/8-inch) diameter, fiberglass injection line). This tubing string terminates just below a packer set at the top of the ore-bearing zone in the fiberglass casing. The lixiviant is injected through a separate 5.08 cm (2-inch) diameter fiberglass tubing string which also terminates just below the packer. Centrali-

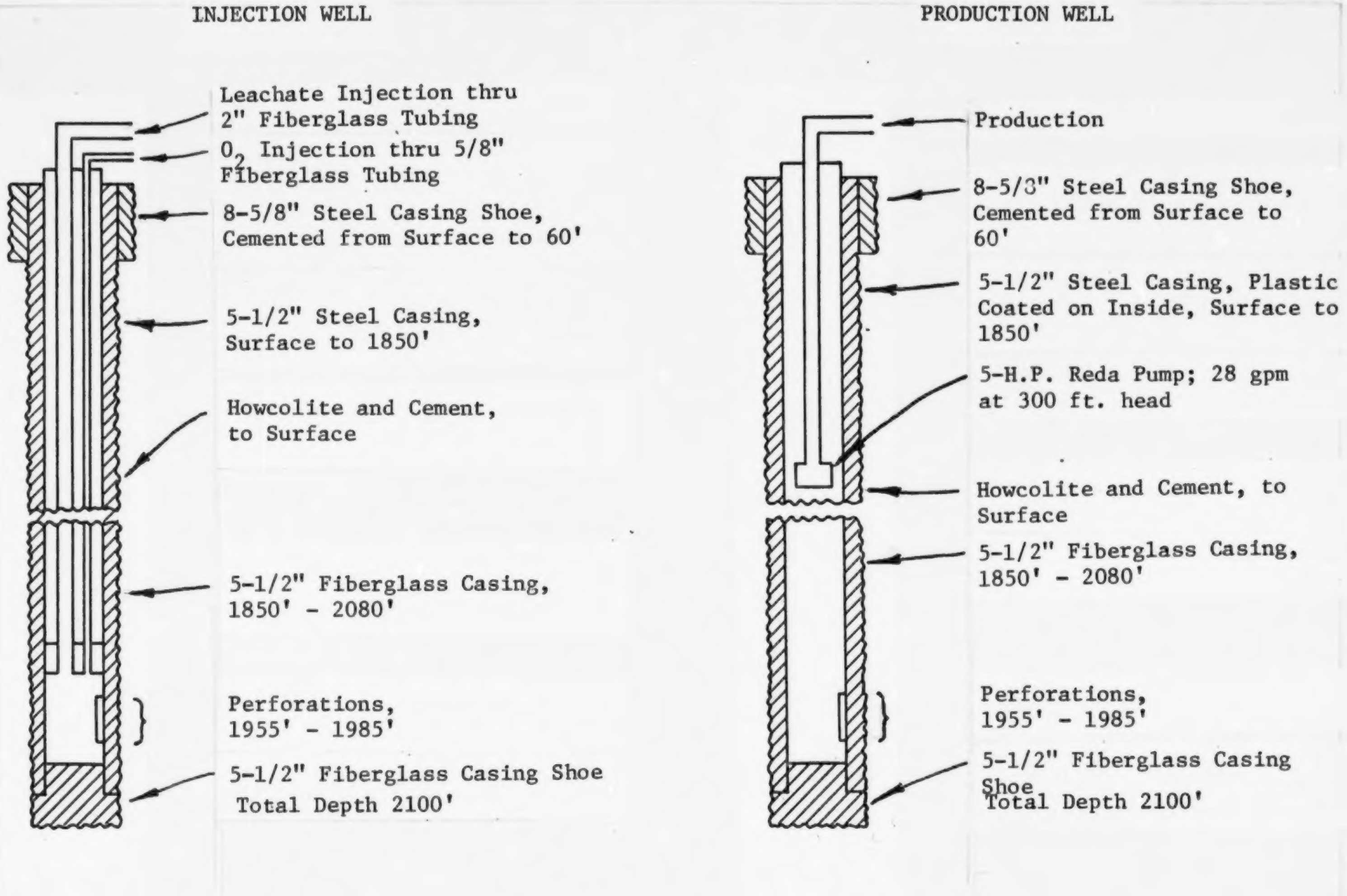

INJECTION WELL
Leachate Injection thru 2" Fiberglass Tubing
O_2 Injection thru 5/8" Fiberglass Tubing
8-5/8" Steel Casing Shoe, Cemented from Surface to 60'
5-1/2" Steel Casing, Surface to 1850'
Howcolite and Cement, to Surface
5-1/2" Fiberglass Casing, 1850' - 2080'
Perforations, 1955' - 1985'
5-1/2" Fiberglass Casing Shoe Total Depth 2100'
PRODUCTION WELL
Production
8-5/3" Steel Casing Shoe, Cemented from Surface to 60'
5-1/2" Steel Casing, Plastic Coated on Inside, Surface to 1850'
5-H.P. Reda Pump; 28 gpm at 300 ft. head
Howcolite and Cement, to Surface
5-1/2" Fiberglass Casing, 1850' - 2080'
Perforations, 1955' - 1985'
5-1/2" Fiberglass Casing Shoe
Total Depth 2100'

Figure 10. Crownpoint Well Completion Design

total depth to surface by circulation of the cement through the casing and up zers are used to center the well casing and the well casing is cemented from the annulus to the surface.

The fiberglass casing opposite the uranium ore-bearing zone is perforated by jet perforators over an interval of 6 to 8 m (20 to 25 feet). The total flooded zone is 18 to 23 m (60 to 75 feet) thick. The zone to be leached is injected with air under pressure prior to mining to improve its permeability. The air pressure, however, must be kept below 6,900 kPa (1,000 psi), in order to avoid shattering the formation. The wells conform with all applicable Federal and New Mexico well completion standards.

The casing design for the production wells is similar to that of the injection wells. However, no packer was used in the production wells. Instead, each well contains a 3.7 kw (5-HP) submersible pump, which is attached to a production tubing string and set several hundred feet below the surface. The production tubing is coated on the inside with plastic to prevent corrosion of the steel by any residual oxidant in the production stream.

Groundwater Effects

The baseline water quality was analyzed in the Crownpoint area and for all wells on the project site when drawdown tests were conducted. Table 10 compares average baseline parameter levels for the aquifers affected by the pilot mine with State and Federal drinking water standards. Table 11 is a summary of various baseline radiation parameters sampled prior to solution mining from wells in the region. High concentrations of natural uranium in the Crownpoint public water supply and the Thoreau public water supply are within EPA established parameters for drinking water in the Grants Mineral Belt (Table 12).

A computer model was developed to simulate underground leachate flow and to calculate the leachate front advance within the ore body during solution mining operations. Reservoir and ore body data were obtained from pumping tests and core analyses which were done in wells on the mine site.

The leachate is produced at about 1.3 L/s (20 gpm) per well. The ion exchange system can accept flow rates as high as 6.3 L/s (100 gpm), but normally runs at about 4.7 L/s (75 gpm). Flow rates for injection and production wells are controlled separately to enable manipulation of the hydraulic balance within the production zone.

During the leaching phase, approximatley 4.6 L/s (73 gpm) of fresh leachate are pumped down the injector wells, and 4.7 L/s (75 gpm) retrieved. The 3% excess is bled to the evaporation pond from the ion exchange to control excess chemical buildup in the lixiviant and to maintain a cone of depression.

The production zone at Crownpoint is in the Westwater "A" and "B" zones which are delineated by shale units within the Westwater member. These shale units confine the movement of liquids in the production zone.

The NMEID has proposed that the following parametric variations which would constitute a significant increase, or potential excursion:

Table 10. Ground Water Quality in the Crownpoint Region

Parameter[a]	Westwater Canyon Mem.	Lower Gallup SDS	Upper & Lower Gallup SDS	New Mexico Ground Water Standards[b] (Jan., 1977)	Nat. Interim Primary Drinking Water Regs. (Dec., 1975)	Rec. Max Permissable Limit for Drinking Water US PHS (1962)
pH (SU)	7.9→8.5	7.0→8.4	8.2→8.3	6-9[a]	-	-
Spec. Cond. (μmhos)	740→1725	510→1150	660	-	-	-
Alkalinity	190	156→220	-	-	-	-
HCO_3	178	178→216	190→194	-	-	-
Ca	3.0→27	0.2→32.0	12→18	-	-	-
Cl	20→64	3.0→7.5	4.6→5.8	250[d]	-	250[f]
F	<0.1→2.5	0.32→0.84	0.45→0.56	1.6[c]	1.4→2.4	1.4→2.4 (0.6→1.7)[f]
Hardness	12→72	1.3→93	50→83	-	-	-
MgNo	0.6→2.0	0.2→8.1	4.9→9.2	-	-	-
No_3-N	-	<0.1→12	<0.1	10[c]	10	45[f]
P	-	0.02→0.10	0.20	-	-	-
K	1.1→7.0	2.4→6.2	1.6→2.3	-	-	-
SiO_2	-	15→54	79	-	-	-
Na	82→419	69→258	120→247	-	-	-
SO_4	48→560	88→420	124→144	600[d]	-	250[f]
Al (μg/l)	<200→300	<100→500	<100	5000[e]	-	-
As (μg/l)	<2→20	<10→10	<10	100[c]	50	50(10)[f]
Ba (μg/l)	<50	<100→100	100	1000[c]	1000	1000
Be (μg/l)	-	<1	<1	-	-	-
B (μg/l)	150→400	150→350	40→200	750[e]	-	1000
Cd (μg/l)	<1	<1	<1	10[c]	10	10
Cr (μg/l)	<5	2→20	3	50[c]	50	50
Cu (μg/l)	<10→30	<1→50	2	1000[d]	-	1000[f]
Cyanide (μg/l)	-	<10	<100	200[c]	-	200(10)[f]
Fe	0.03→2.00	<0.1→2.5	0.39	1.0[d]	-	0.3[f]
Pb (μg/l)	<10→14	<1	<1	50[c]	50	50
Li (μg/l)	10→20	40→60	-	-	-	-
Mn (μg/l)	<10→20	<10→100	51	200[d]	-	50[f]
Hg (μg/l)	<0.2	<0.2	<0.4	2[c]	2	-
Mo (μg/l)	60→1330	<1	<1	1000[e]	-	-
Ni (μg/l)	<50	<10	<10	200[e]	-	-
Phenols (μg/l)	-	<1	-	5[d]	-	1[f]
Se (μg/l)	<1→1	<1	<10	50[c]	10	10
Ag (μg/l)	<10	<1	<1	50[c]	50	50
V (μg/l)	<50	<10	<10	-	-	-
Zn (μg/l)	<10→100	42→500	92	10,000[d]	-	5,000[f]
TDS	300→1249	400→780	427→748	1000[d]	-	500[f]
Co (μg/l)	<5	<1	<1	50[e]	-	-

a. Parameters reported as mg/l unless noted otherwise.
b. When an existing pH or concentration of any contaminant exceeds the standard specified, the existing pH or concentration shall be the allowable limit. These standards shall apply to the dissolved portion of the contaminant, with the exception of mercury (total).
c. Standards for human health (primary).
d. Standards for domestic water supply (secondary).
e. Standards for irrigation use, also includes human health and domestic water supply standards.
f. Recommended limit for drinking water.
g. For waters used continuously on all soil.

Table 11. Radiation Levels of Groundwater in the Crownpoint Region

Sampling Location	Date Collected	Gross α (pCi/l)	Gross β (pCi/l)	U (μg/l)	Th^{230} (pCi/l)	Dissolved Ra^{226} (pCi/l)
Anasazi; stock tank in Section 16 E	11/04/75	0.1 ±0.3	2.9 ±0.6	0.21	--	40±20 0.21
	05/11/76	--	--	0.70	0.1 ±0.1	0.31
	08/28/76	--	--	0.056	0.7±0.1	0.18±0.02
	11/08/76			0.33	0.6±0.1	0.28±0.02
Well 4U9; Section 4 NE	11/04/75	±0.2 ±0.3	4.6 ±0.6	0.05	--	130±20 0.52
	05/12/76	--	--	0.73	±0.1 ±0.1	0.79
	08/28/76	--	--	0.14	1.1±0.2	0.45±0.03
	11/08/76			0.16	2.9±0.3	1.02±0.04
Well 17-1650351; Section 4 SW	11/04/75	--	--	0.06	--	0.85
	05/12/76	--	--	0.29	±0.1 ±0.2	0.14
	08/28/76	--	--	0.64	0.6±0.1	0.38±0.02
	11/08/76	--	--	0.23	0.3±0.1	0.72±0.03
Crownpoint public water supply	11/05/75	1.0 ±0.4	2.1 ±0.6	3.4	--	90±20 0.19
	05/12/76	--	--	4.7	0.4 ±0.3	0.18
	08/28/76	--	--	7.4	1.8±0.2	0.29±0.02
	11/08/76	--	--	5.2	2.2±0.2	0.27±0.02
Thoreau public water supply	05/12/76	--	--	7.8	0.0 ±0.2	0.20
	08/28/76	--	--	7.0	1.3±0.2	0.37±0.02
	11/08/76	--	--	8.2	2.0±0.2	0.23±0.02
Well 8U12; Section 8 NE	11/04/75	--	--	0.03	--	0.78^{c}
Well 4U60; Section 4 NE	08/28/76	--	--	0.095	1.2±0.2	0.6±0.03

Table 12

Groundwater Quality in the Grants Mineral Belt[1]

Background Levels in Groundwater

Radionuclide	Range	Average
Radium-226	0.060 - 0.310 pCi/l	0.160 pCi/l
Polonium-210	0.270 - 0.570 pCi/l	0.360 pCi/l
Thorium-230	0.013 - 0.051 pCi/l	0.028 pCi/l
Thorium-232	0.010 - 0.024 pCi/l	0.015 pCi/l
Natural U	21 to 100 ug/l	52 ug/l

Radium and Gross Alpha Concentrations for Municipal Water Supplies

Location	Radium-226	Gross Alpha
Grants	0.42 ± 0.02[2]	19 ± 13[2]
Milan	0.14 ± 0.01	12 ± 10
Bluewater	0.22 ± 0.01	8 ± 10
Gallup	0.68 ± 0.03	10 ± 9
Paguate	0.18 ± 0.02	2 ± 4
Churchrock	0.12 ± 0.01	3 ± 7

---

[1] Data extracted from ORP/LV-75-4, US EPA

[2] All error terms are at the 95 percent confidence level.

from: Mobil Oil Corp., 1978.

Conductivity: a 25 percent increase above the highest baseline value of all the wells,
Uranium: a 5 mg/L increase above the baseline value, and
Sulfate: a 10 mg/L increase above the baseline value.

Biweekly data reports are filed for pH, conductivity, sulfate, uranium, molybdenum, sodium, gross alpha and gross beta values in the monitor wells. In the latest available quarterly report (covering November, 1979, through January, 1980), the operators stated that none of the permitting criteria had been exceeded.

Processing and Waste Disposal

The uranium is extracted from the pregnant liquor by an ion-exchange process. The barren lixiviant goes from the ion-exchange adsorption column to a surge tank, where additional CO_2 and NaOH are added before reinjection to the ore body. The 0.06 to 0.13 L/s (1 to 2 gpm) bleed stream to the evaporation pond (Figure 11) makes up 75% of all discharges entering the pond. A small portion of this bleed stream also enters the elution circuit and is eventually disposed of as excess decant. This stream contains up to 5 ppm U_3O_8.

The loaded resin is transferred to the elution column where the uranium is stripped from the resin. The fresh resin is returned to the top of the loading column to repeat the circuit. An acid regeneration system was installed in this loop to remove calcite from the resin. Pregnant eluate is composed of:

Constituent	Concentration Range (ppm)
Chloride	20,000 - 30,000
Carbonate	2,000 - 5,000
Bicarbonate	10,000 - 20,000
Sodium	20,000 - 30,000
Sulfate	1,000 - 3,000
Calcium	50 - 300
Uranium	6,000 - 15,000

A circuit takes the precipitate and the decant to a thickener where a spiral classifier stirs the precipitate at the bottom and the barren eluent floats to the top as a decant. The decant is stored and regenerated before being returned to the elution column. A small percentage (0.06 L/s or 1 gpm) is bled to remove excess NaCl and diverted to the evaporation pond.

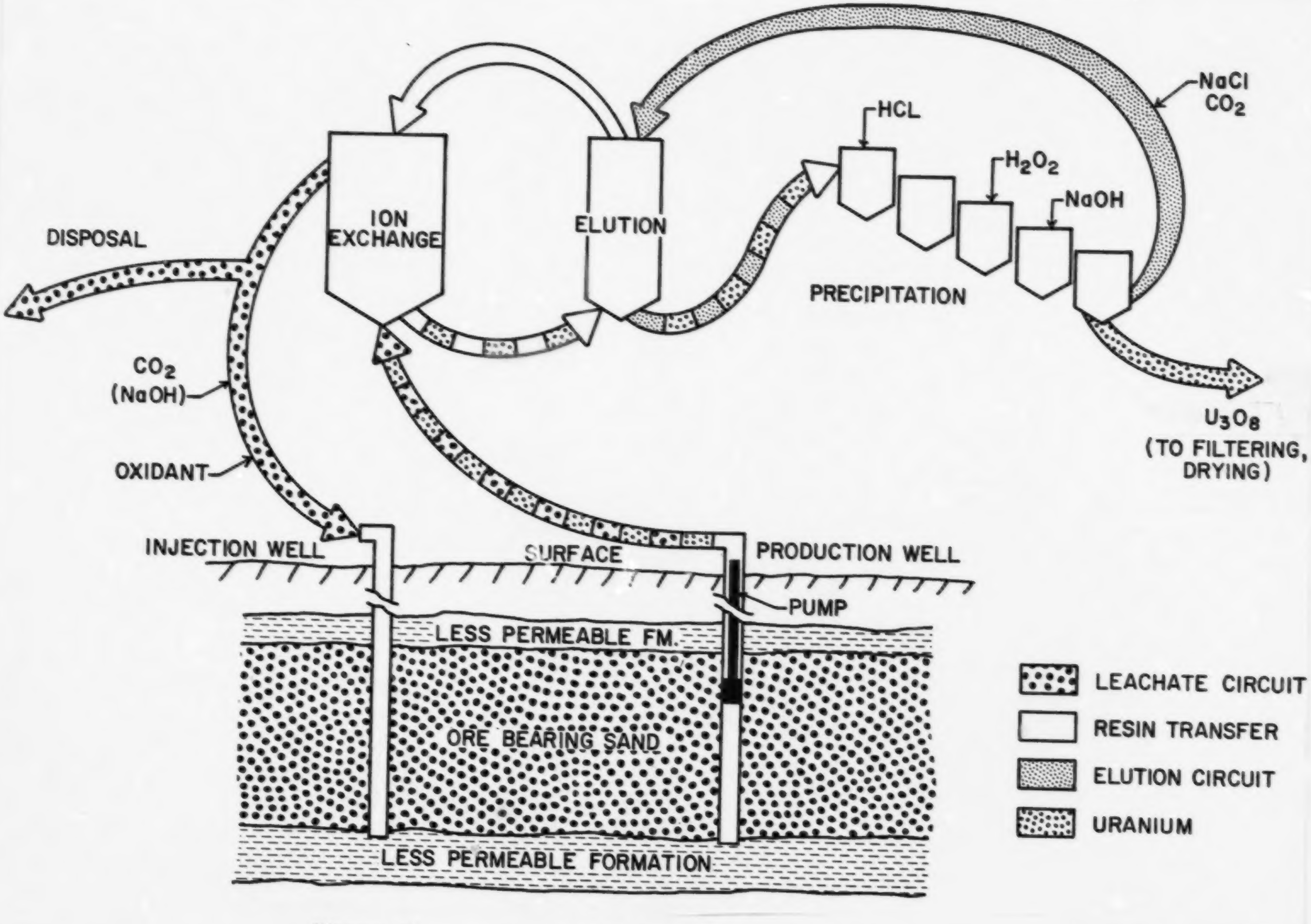

ION EXCHANGE
ELUTION
HCL
H_2O_2
NaOH
NaCl
CO_2
PRECIPITATION
DISPOSAL
CO_2
(NaOH)
OXIDANT
U_3O_8
(TO FILTERING, DRYING)
INJECTION WELL
SURFACE
PRODUCTION WELL
PUMP
LESS PERMEABLE FM.
ORE BEARING SAND
LESS PERMEABLE FORMATION
LEACHATE CIRCUIT
RESIN TRANSFER
ELUTION CIRCUIT
URANIUM

Figure 11. Crownpoint Process Plant Flow Chart

An evaporation pond is located just west of the well field and processing facilities (Figure 9). Total pond capacity is approximately 7.6 million liters (2 million gallons), which can accept flow rates of 0.32 L/s (5 gpm) for one year. This figure is over twice the bleed stream rate from the lixiviant and elution circuits. The pond will also provide extra disposal capacity in the event of a lixiviant excursion in the well field, or spills anywhere in the process circuit. It also provides a site for the disposal of chemicals from the testing lab and brine from the reverse osmosis unit during restoration. The surface area of the pond is designed to evaporate 0.15 L/s (2.3 gpm) liquid at half volume.

The evaporation pond leak detection system consists of a riser from the PVC drain underlying the pond and four shallow wells at the lagoon perimeter. Water samples from these are analyzed bi-weekly for uranium, sodium, bicarbonate, and conductivity. No excursions have occurred since plant operations began.

Restoration

The 14-month restoration phase of the Crownpoint Section 9 pilot plant began in November, 1980. The New Mexico Environmental Improvement Division (NMEID) requires that the 27 parameters for drinking water standards be returned to near-baseline conditions.

Restoration is being accomplished by withdrawing groundwater from the leach zone aquifer at 4.4 L/s (70 gpm), passing it through the ion-exchange unit and then running the effluent through a reverse osmosis unit. The clean water, or permeate, is then reinjected.

The permeate leaving the reverse osmosis unit for reinjection is monitored every hour at a small testing laboratory on the mine site. Chloride and molybdenum levels are tested by titration to insure that the water is of sufficient quality to be injected to an aquifer used for drinking water. A composite sample from every shift goes to a larger laboratory near Crownpoint at Mobil's Nufuels field office for a re-check. Mobil will sample the permeate stream biweekly to determine values for the existing excursion monitoring parameters of conductivity, uranium, sulfate, molybdenum, and sodium. A quarterly analysis will include testing of all parameters required by the State of New Mexico Water Quality Control Commission Regulations, plus gross alpha, gross beta, Ra^{226}, Ra^{228}, combined Ra^{226} and Ra^{228}, Th^{230}, Pb^{210}, spcific conductance, and alkalinity. Brines recovered from the reverse osmosis unit are pumped to the evaporation pond for disposal.

6.2 THE EL MESQUITE MINE, DUVAL COUNTY, TEXAS

Introduction

The El Mesquite Mine of the Mobil Oil Corporation is located on 906 ha (2,240 acres) of land in Duval County, 6.4 km (4 miles) east of Bruni, Texas (Figure 12). Forty-five production zones have been defined; they range in size from 0.97 to 14 ha (2.4 to 35 acres), within the property.

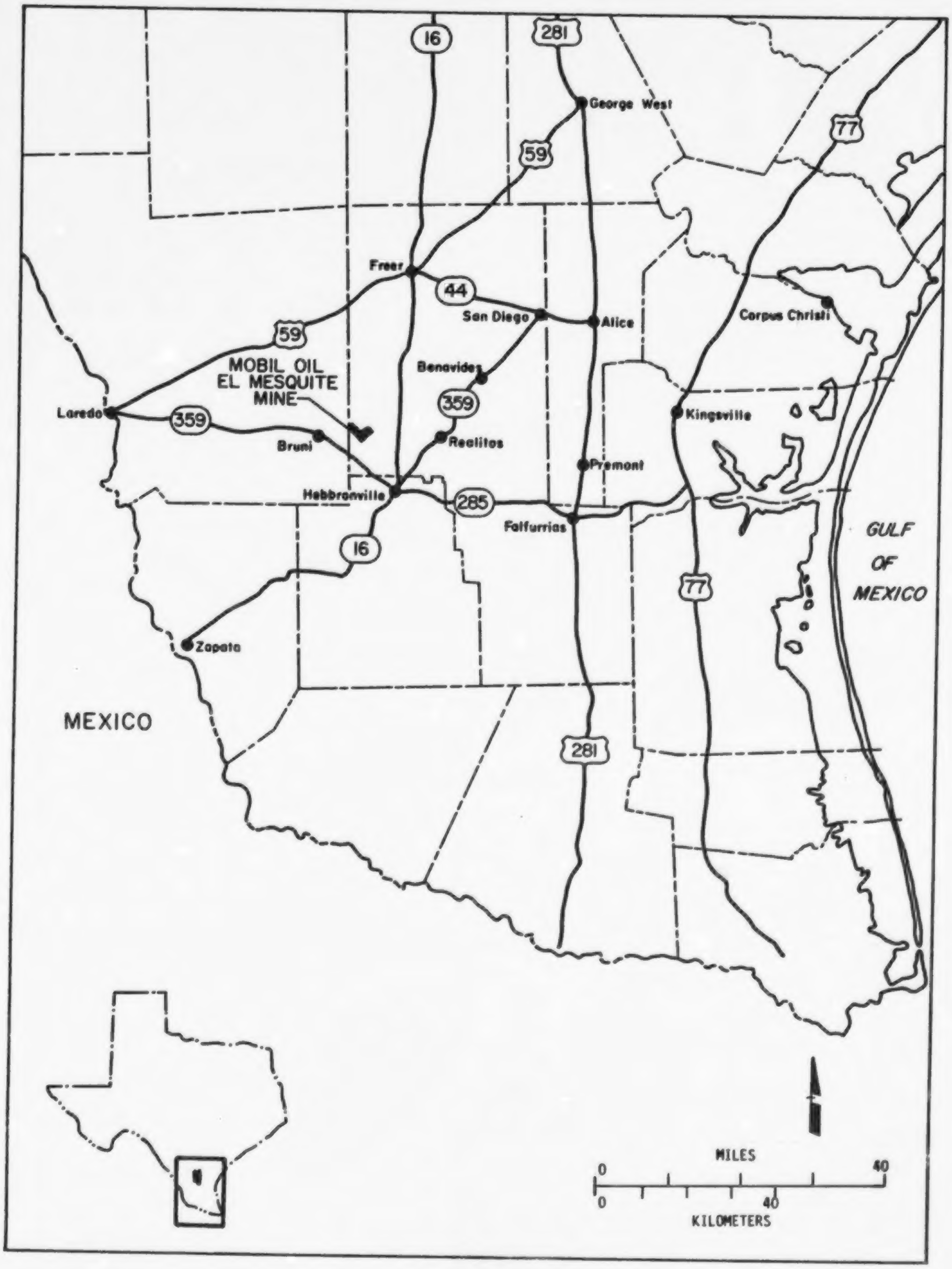

16
281
George West
59
77
Freer
44
San Diego
Alice
Corpus Christi
59
MOBIL OIL
EL MESQUITE
MINE
Benavides
359
Laredo
359
Bruni
Realitos
Kingsville
Premont
Hebbronville
285
Falfurrias
16
GULF
OF
MEXICO
77
Zapata
MEXICO
281
MILES
0
40
0
40
KILOMETERS

Figure 12. Location Map, El Mesquite Mine

Exploration leading to the development of the El Mesquite Mine began in 1969 at the O'Hern lease. During the ensuing years, new leases were added until the total lease block encompassed 3,240 ha (8,000 acres), of which 906 ha (2,240 acres) were named the El Mesquite property.

Exploration was followed by injection and production flow-rate tests using water. In 1975, a pilot plant was constructed on the O'Hern property. It was started as an 5 L/s (80 gpm) operation and scaled up to higher flow rates of 32 L/s (500 gpm). In 1977, well field development began and in mid-1978 plant construction was initiated. The project was completed and brought into production September 18, 1979.

The El Mesquite Mine site lies within the Gulf Coastal Plain physiographic province. This area is characterized by low rolling hills with maximum relief at the mine site less than 10 meters (30 feet). Red-brown fine to medium grained Holocene sands cover fifty percent of the mine site with the remainder consisting of outcrops of the Goliad Sand, of Late Pliocene age. Vegetation in the mine area consists of a thick growth of mesquite, sage, mountain laurel and cactus.

The uranium ore deposits occur in the Soledad Conglomerate, or middle member, of the Catahoula Formation of Miocene age. The Soledad Conglomerate averages 76 m (250 feet) in thickness within the mine area. It consists of interbedded gravels, sands and minor shale beds all of which were deposited in a fluvial environment. The major production horizon is restricted to a 15 to 24 m (50 to 80 foot) thick zone composed of interbedded sands with local shale lenses. The sands range in grain size from fine to medium. Both sands and clays are highly tuffaceous. The lower member, or Fant Tuff, averages 152 m (500 feet) thick in the Bruni area. It is comprised of tuffaceous silt and silty clay with lenses of fine to very fine sand. This member is a major aquitard and has been recognized in the past as water of useable quality.

The Soledad Conglomerate is overlain by the Chusa Tuff, a clay-rich unit which functions as an aquiclude at the mine site. The Catahoula Formation is underlain by the Frio Formation. This formation was not encountered during drilling and was not expected to be affected by leaching of the uranium ores in the overlying Catahoula Formation.

The mine area is situated along the northeast flank of the Rio Grande Embayment. Sediments dip east-southeast at one to two degrees 20-40 m/km (100 to 200 feet per mile). The only known notable structural features within Duval County are three small growth faults with less than 61 m (200 feet) of throw. These strike northeast-southwest and dip steeply to the southeast. They do not intersect the mine site.

The drainage basin upgradient from the mine lies partly in Duval County and partly in Webb County to the west. All stream channels within the mine area are dry except during and briefly following periods of heavy rainfall. Mesquite Creek is the only intermittent stream that crosses the mine area. The mine lies in an "undefined" area, for which insufficient data are available to allow use of available analytical methods for estimating flows in ungauged watersheds.

Groundwater

Fresh to moderately saline groundwater occurs in three stratigraphic horizons within Duval County. The three aquifers are located in the Catahoula Sand, the Oakville Sandstone, and the Goliad Sand. The aquifers are generally confined except at shallow depths in the outcrop areas. At the mine site the Oakville Sandstone is absent, the Catahoula and Goliad Sands constituting the only aquifers.

In general, groundwater movement within the region is to the southeast. The average gradient is 2.1 m/km (11 feet per mile). Centers of heavy pumping by municipalities and ranchers have locally altered the regional gradient. Average groundwater velocity is approximately 463 mm (0.152 ft) per day.

As only regional-scale hydrologic information was available for the mine site, Mobil conducted detailed hydrolic studies of each production area prior to operation. These tests indicated that there are no boundary conditions and there do not appear to be any significant variations in permeability over the subject area. The mean permeability is 282 millidarcies. A slight increase of permeability, however, was noted within the production area. It was felt that because of their fluvial origin, the sediments would vary widely in local permeability. Tests of cased wells in the underlying aquifers indicated no hydrologic interconnection within aquifers during the above pumping test. No overlying confined aquifers were detected during these investigations.

Baseline values of water quality for the mine area and each production zone were established prior to solution mining. In addition, water quality was analyzed from all domestic water wells within a two-mile radius of the mine. Table 13 shows values of baseline water quality compiled from samples taken from regional wells. The wells were not selected geometrically, but rather so as to provide the maximum amount of data on the geochemistry of the groundwaters within the mine area.

In general, the regional groundwater quality in the mine area is variable due to the presence of differing geochemical environments in the subsurface. Groundwater from reduced zones is of significantly better quality than that from oxidized zones.

The fact that the quality groundwater was found to vary regionally established the need to monitor groundwater quality within each production zone, as final restoration values generally must be within 10% of baseline values.

Table 14 summarizes the baseline water quality for the EOA #1 production zone. Note the major differences in several parameters when compared with the regional values. Metals, in particular, vary in abundance over several orders of magnitude, which reflects the presence of reducing conditions in the production zones.

Table 13. Baseline Groundwater Quality in Region of El Mesquite Mine

Constituent	
Calcium	18.18 mg/l
Magnesium	5.50 mg/l
Sodium	348.68 mg/l
Potassium	7.63 mg/l
Carbonate	5.20 mg/l
Bicarbonate	265.75 mg/l
Sulfate	86.65 mg/l
Chloride	420.32 mg/l
Fluoride	0.74 mg/l
Nitrate	20.60 mg/l
Ammonia	0.41 mg/l
Arsenic	0.02 mg/l
Barium	0.20 mg/l
Boron	1.58 mg/l
Cadmium	0.01 mg/l
Chromium	0.03 mg/l
Copper	0.02 mg/l
Iron	2.48 mg/l
Lead	0.05 mg/l
Manganese	0.05 mg/l
Molybdenum	0.30 mg/l
Nickel	0.02 mg/l
Selenium	0.01 mg/l
Silica	19.86 mg/l
Silver	0.02 mg/l
Uranium	0.11 mg/l
Vanadium	0.20 mg/l
Zinc	0.03 mg/l
Radium 226	4.39 pCi/l
pH	8.09 std.
TDS	1,120.25 mg/l
Conductivity	1,894 umhos
Alkalinity	221.25 std.

SOURCE: Mobil Oil Corp., 1979.

Table 14. Baseline Water Quality, EOA #1 Production Zone
El Mesquite Mine

Parameter	Average Value (9 wells)	Unit
Calcium	6.16	mg/L
Magnesium	0.79	"
Sodium	382	"
Potassium	7.96	"
Carbonate	6.4	"
Bicarbonate	234	"
Sulfate	58	"
Chloride	423	"
Fluoride	0.50	"
Nitrate-N	2.8	"
Silicon	17.5	"
pH	8.43	Std.
TDS	1071	mg/L
Conductivity	1885	μmhos
Alkalinity	202.8	Std.
Arsenic	0.007	mg/L
Barium	0.117	"
Boron	0.925	"
Cadmium	0.0005	"
Chromium	0.0046	"
Copper	0.015	"
Iron	0.12	"
Lead	0.119	"
Manganese	0.014	"
Mercury	0.0002	"
Nickel	<0.01	"
Selenium	0.004	"
Silver	<0.01	"
Zinc	0.024	"
Ammonia	0.023	"
Uranium	0.039	"
Molybdenum	0.015	"
Vanadium	0.03	"
Radium 226	3.20	pci/L

SOURCE: Mobil Oil Corp., 1979.

The Mine Plant

The production facilities consist of a well field, a processing plant, storage tanks, shops and offices. The plant was originally designed to process 130 L/s (2,000 gpm), but with more efficient operation can now operate at 200 L/s (3,200 gpm). Design production capacity is 295,000 kg/yr (650,000 lb/yr) of yellow cake.

The well field consists of 45 production areas. Each area is surrounded by production zone monitor wells and includes several shallow monitor wells. Production and injection wells are drilled on staggered straight lines with an average distance of 21 m (70 feet) between injection wells. This is more commonly known as the five spot pattern with four injection wells at the corners of a square centered on a production well.

All production and injection wells are completed in the middle Catahoula Formation, at depths ranging from 91 to 275 m (300 to 900 feet). There are surface gravels overlying the well which are monitored by shallow wells. Aquifers underlying the well field are not monitored, as the clay of the lower Catahoula serves as an aquiclude.

Production and injection wells normally are cased with 11.43 cm (4-1/2 inch) fiberglass tubing. The completion technique for these wells includes drilling the wells through the completion interval, running casing to total depth and cementing the annulus back to the surface. Three centralizers are run on the casing string, evenly spaced across the sand intervals. The wells are screened at the producing intervals.

Monitor wells are cased with PVC, fiberglass, or steel casing, dependent on completion depth. Monitor wells are drilled through the desired completion interval, and the casing is run with a wire-wrapped screen on the bottom, a double cement basket above the screen, and three centralizers evenly spaced across the sand intervals. It is then cemented to the surface.

The extraction of uranium involves the following: leaching, ion exchange, elution, precipitation, dewatering, packaging and shipping. Uranium minerals are leached in situ from the sand host by a lixiviant solution composed of a bicarbonate anion complexing agent (CO_2 or soda ash) and oxygen. It is expected up to 15 pore volumes of leach solution will be necessary to recover the easily leachable uranium. Produced fluids pass from the production wells into surge tanks and from the surge tanks into one of five ion-exchange trains, each equipped with three 10.3 m^3 (365 ft^3) columns, from which the uranyl tricarbonate complex is adsorbed by ion exchange.

The barren leach solution passes to recharge tanks, through sand filters, and then is reinjected into the formation for a new leach cycle. The loaded resin is transferred to an elution column and stripped of uranium through the addition of sodium chloride. The stripped resin is returned to the ion exchange column and the pregnant eluate, containing 15,000 to 20,000 ppm uranium, is precipitated by the addition of hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2). The resultant uranium slurry is then washed, thickened until the uranium content increases to about 30%, and subsequently centrifuged until it reaches 50-60%. This product is dried in an oil-fired dryer to reduce moisture in the yellowcake to 1 to 2%. The yellowcake is then loaded into 208 L (55 gal) drums for shipping.

Restoration

Mobil has announced the planned restoration at El Mesquite, but has not released specific information on the proposed method of aquifer restoration. They have provided a restoration progress report for the adjacent O'Hern well field, which is considered to be geologically and hydrologically similar.

At O'Hern, Mobil used the groundwater sweep method. Table 15 presents the analytical results of a three-month test conducted after the formation had been flushed with 3.5 pore volumes of water. Ammonia test restoration values were not reported. With few exceptions, all measured parameters were within 25% of their initial baseline values. Ammonia and nitrates, not reported, are thought to be considerably above the original baseline conditions.

Excursions

On November 28, 1979, Mobil Oil formally notified the Texas Department of Water Resources (TDWR) of a leachate excursion at its El Mesquite Mine. Two monitor wells showed significant increases in conductivity, SO_4, U_3O_8 and HCO_3 (Table 16) during the normal bimonthly sampling on November 27. Immediate corrective action was initiated. Seven injection wells were shut down and three of these wells were converted to production wells. Sampling and analysis of water from monitor wells were conducted every other day.

During the subsequent week, a total of 15 injection wells were shut down with three continuing as production wells. When the piezometric surface had dropped sufficiently to induce a gradient back into the production area, 10 wells were reactivated at reduced injection rates. By the end of the second week both monitor wells were below the upper clean-up limits specified by TDWR for all parameters except bicarbonates. On December 21, 1979, Mobil notified the TDWR of its intent to return to bimonthly sampling for one of the two wells, as the results of analyses from five consecutive samples had been below the specified upper limit. One week later, the second well was taken off excursion status and the mine was returned to normal injection and pumping status.

On January 23, 1980, Mobil notified the TDWR of a second excursion in another production area. One monitor well showed significant increases in conductivity, SO_4, and HCO_3 (Table 17). Three injection wells were immediately shut down and a fourth converted into a production well. In addition, production rates were increased in four other wells. Within three weeks, values had returned to baseline levels and the well was taken off excursion status. No additional excursions had been reported by January, 1981.

6.3 THE IRIGARAY MINE, JOHNSON COUNTY, WYOMING

Introduction

The development of this mine has taken place over a period of approximately seven years, since 1974. Its history involves modifications to the operation to overcome environmental and technical problems and thus serves as an example of complex relationships that can exist among mining operations, ambient conditions, regulatory bodies, and public concerns. These relationships are summarized in this section.

Table 15. Restoration Test Results for the O'Hern Project

	Non-Ammonia Test Means*	Non-Ammonia Test Final Restoration*
Calcium	11.27	21
Magnesium	3.02	4
Sodium	305.83	338
Potassium	10.87	8.1
Carbonate	5.67	3
Bicarbonate	374	369
Sulfate	118	180
Chloride	210.67	216
Fluoride	0.65	0.6
Arsenic	0.027	0.061
Barium	0.61	0.065
Boron	1.73	1.115
Cadmium	0.1	0.0003
Chromium	0.03	0.003
Copper	0.02	0.007
Iron	0.77	0.04
Lead	0.05	0.002
Manganese	0.023	0.022
Mercury	0.3	0.5
Molybdenum	0.14	0.01
Nickel	0.02	0.01
Selenium	0.01	0.007
Silica	45.33	40
Silver	0.02	0.01
Uranium	2.36	1.7
Vanadium	0.2	0.045
Zinc	0.023	0.015
pH	8.23	8.35
TDS	909.5	1036

*Average UI-94 & UI-95

SOURCE: Mobil Oil Corp., 1979. All units in mg/L except for pH.

Table 16. Excursion of November 27, 1979, El Mesquite Mine

	Conductivity	SO_4	U_3O_8	HCO_3	Ca	Cl
Upper Limit	1875	138	5.3	424	10	321
Well UI 974	2100	155	2.8	544	3	245
Well UI 973	1850	145	30.9	458	6	245

Underlined values are in excess of exceptable upper limit.

SOURCE: Mobil Oil Corp., 1979a; units in mg/L.

Table 17. Excursion of January 23, 1980, El Mesquite Mine

	Conductivity	SO_4	U_3O_8	HCO_3	Ca	Cl
Upper Limit	1875	138	5.3	424	10	32'
Well UI-714	2100	220	0.4	519	8	240

Underlined values are in excess of exceptable upper limit.

SOURCE: Mobil Oil Corp., 1980; units in mg/L.

The geology of the Irigaray Site and three other uranium deposits in Wyoming and South Dakota was described generally as "normal western sandstone," consisting of sandstone beds below the water table, some 15 to 30 m (50 to 100 ft) thick and overlain and underlain by impermeable shale beds. The porosity was characterized as being about 30%, with lateral permeabilities of 200 to 400 millidarcies (md) and vertical permeabilities of 10 to 100md. The ore occurred in zones between oxidizing and reducing mineral facies in channel deposits of the Wasatch Formation, of Eocene Age. The dip of these beds was about 2° W at Irigaray. Thickness ranged from 30 to 43 m (100 to 140 ft). The ore occurred in mineralized bands about 24 m (8 feet) thick (Figure 13).

Proposed Operation

On March 29, 1974, Wyoming Mineral Corporation filed an environmental report to support its application for a license to operate a research and development (R&D) solution mine for uranium, at Irigaray, Wyoming (Wyoming Mineral Corporation, 1974, Figure 14). This pilot operation was to occupy approximately one acre of land, on which a four-spot pattern of three injection wells and one production well was to be situated. A carbonate lixiviant was to be injected at a rate of approximately 1.6 L/s (25 gpm), for a volume of about 140,000 l (37,000 gallons) in the ore zone and 56,8000 l (15,000 gallons) in the plant at any one time. It was estimated that 60 cycles of fluid exchange through the entire circuit would be involved, for a total volume of some 11 million liters (3 million gallons). It was expected that about 1,300 kg (3,000 pounds) of U_3O_8 would be produced from this pilot operation. The processing plant was modular and contained in trailers (Figure 15). As no processing was was to be produced, no tailing's ponds were planned.

Surface water at the site was to be protected by bentonite clay liners in surge pools and dikes surrounding the processing plant. A pattern of 3 monitor wells was laid out to provide information on the lateral extent of the zone affected by the mining operation (Figure 15).

The expected composition of the pregnant solution was estimated to be as shown in Table 18. The pregnant solution was to be processed in ion-exchange columns, where the uranium would be extracted. Approximately 3 to 7 ppm of U_3O_8 was expected to remain in the barren solution leaving the ion-exchange columns. The carbonate lixiviant was to be reconstituted at a mixing tank to the required pH (6 to 10), after which it was to be reinjected.

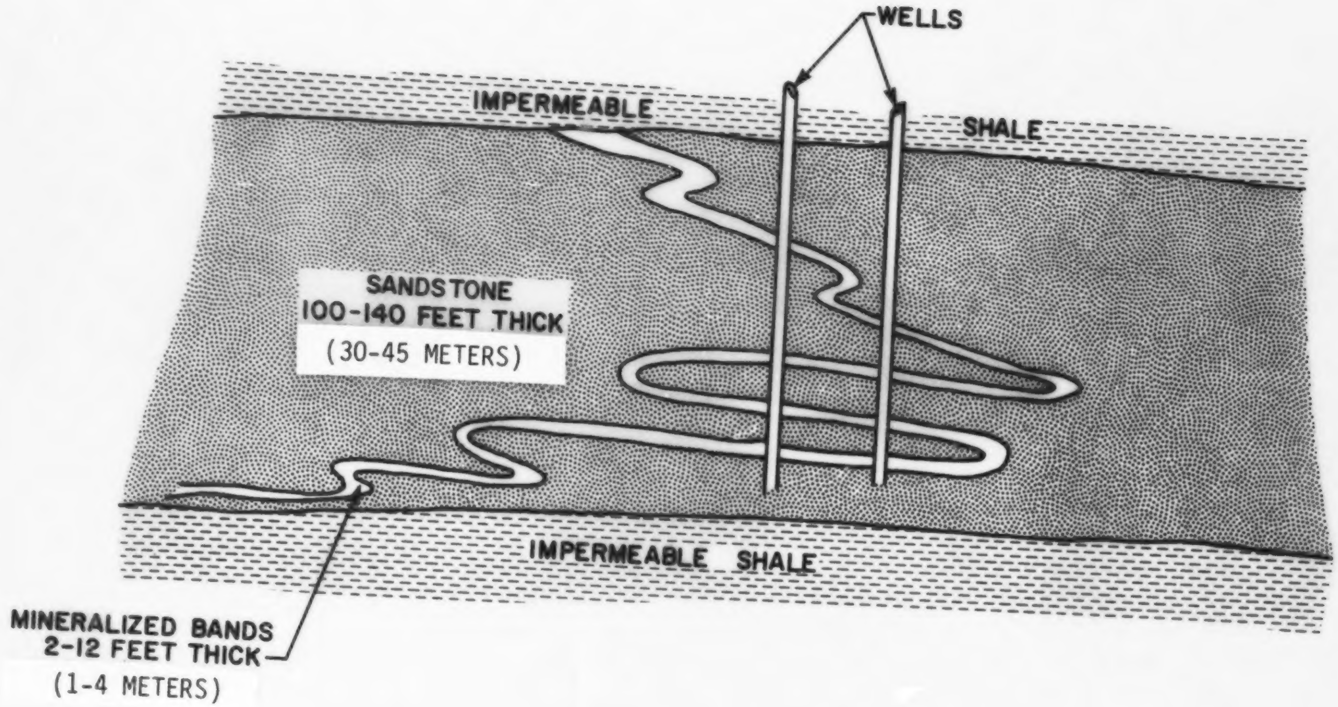

WELLS
IMPERMEABLE
SHALE
SANDSTONE
100-140 FEET THICK
(30-45 METERS)
IMPERMEABLE SHALE
MINERALIZED BANDS
2-12 FEET THICK
(1-4 METERS)

Figure 13. Generalized Geologic Cross-Section, Irigaray Mine

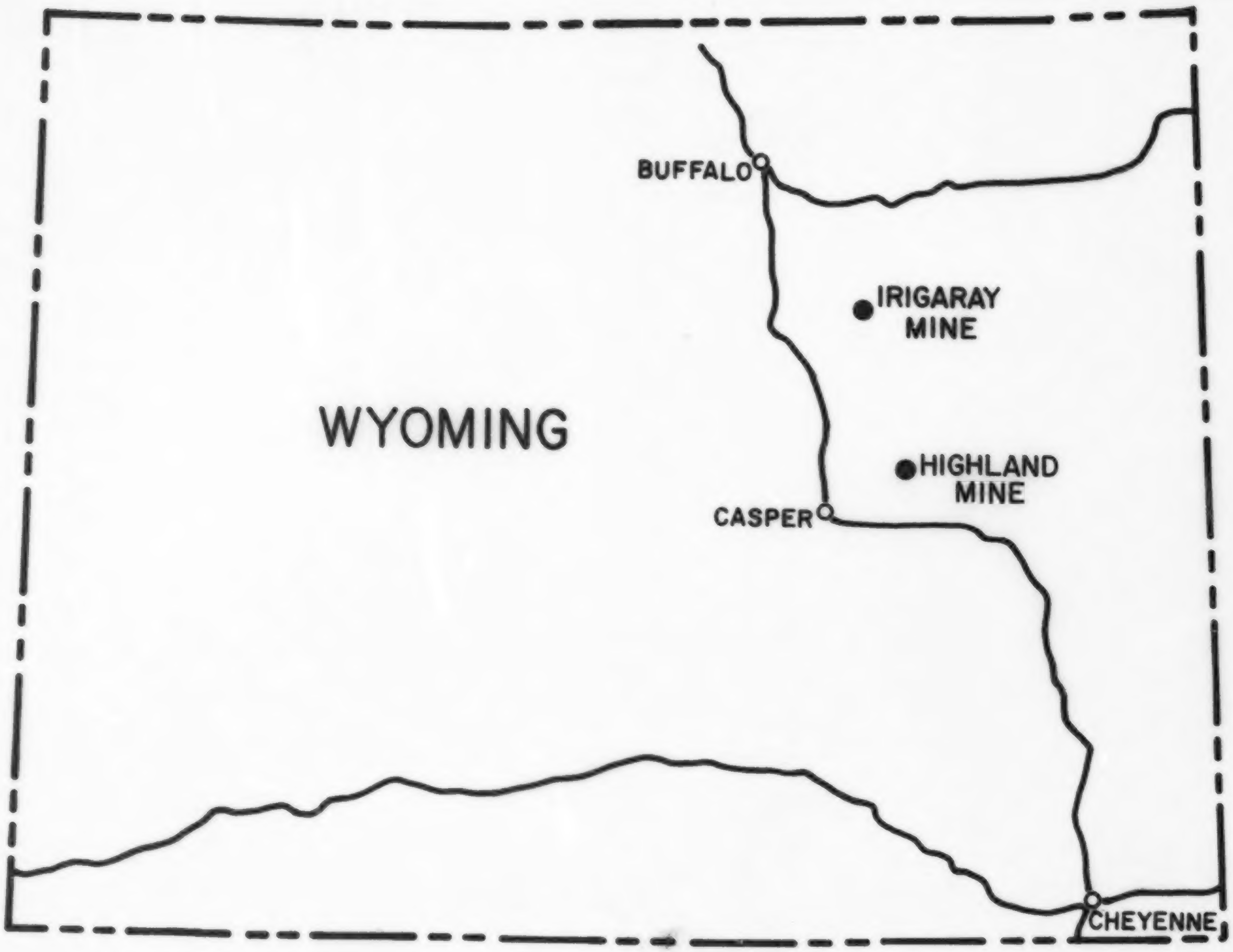

WYOMING
BUFFALO
IRIGARAY MINE
HIGHLAND MINE
CASPER
CHEYENNE

Figure 14. Location Map, Irigaray and Highland Mines

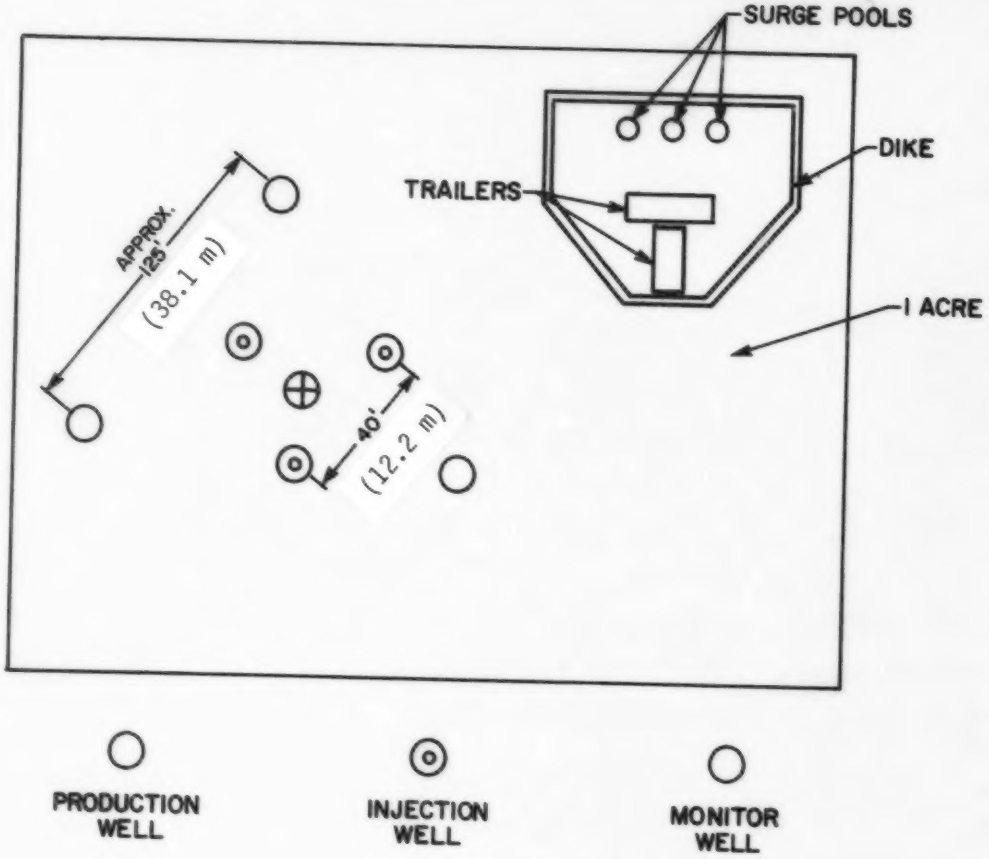

SURGE POOLS
DIKE
TRAILERS
I ACRE
APPROX. 125'
(38.1 m)
40'
(12.2 m)
PRODUCTION WELL
INJECTION WELL
MONITOR WELL

Figure 15. Pilot Plant Arrangement at the Irigaray Mine

Table 18. Expected Composition of Pregnant Liquor, Irigaray Mine

U (as U_3O_8)	1 g/L
Basic strength (as HCO^-_3)	50 g/L
pH	6-10
Ca^{++}	0.5 g/L
NH_4^+	0.2 g/L

The loaded resin was to be eluted by chloride ions, with an expected efficiency of stripping of 95%. Precipitation was to be attained by the addition of HCl to lower the pH to about 2, driving off any dissolved CO_2; followed by the addition of ammonia, to neutralize the pH and to cause ammonium diuranate to precipitate. The resulting yellowcake would be a slurry of about 50% solids. The processing circuit was shown schematically as in Figure 16. The only effluent stream expected from this pilot plant was uranium concentrate. A daily production of approximately 20.4 kg (45 pounds) was anticipated.

Wyoming Mineral Corporation cited their experience in Texas to support their position that no excursions would occur at the Irigaray research and development plant. Safeguards against excursions were provided by cementing of the wells to the mineralized zones, and perforating or slotting the casing in the ore zone only. They felt that little if any negative impact on the environment would occur because of the presence of existing carbonate systems in groundwater, and placed reliance on dilution and buffering by the existing calcite system to maintain natural pH values.

Monitored wells were to be sampled daily for pH, Eh, HCO^-_3, and U_3O_8. Wells and streams within a 8 km (5-mile) radius were to be samples one month prior to the operation and twice afterward (at 3-month intervals) for pH, Eh, U, V, Mo, Se, As, and alpha and beta activity.

The research and development operation commenced in November, 1975, and lasted until October, 1976. The results of tests during this pilot operation showed that optimum well spacing for the site was about 12.2 m (40 feet), and that a 7-spot configuration in a hexagonal array was best suited for the operation.

Restoration tests, which began in May, 1977, indicated that sweeping of the production zone by clean, injected water reduced most contaminants in the groundwater. Flusing of the production zone by concentrated solutions of Ca, Na, or Mg brought NH_4^+ levels down to 120 ppm. Neither method, however, was satisfactory in removing NH_3 from the formation. Reverse osmosis treatment of the extracted water, followed by reinjection, was able to reduce the NH_4^+ content of the formation water to 35 ppm (USNRC, 1978).

A Final Environmental Statement relative to Wyoming Mineral Corporation's application for a license to operate on a commercial scale was issued by the U.S. Nuclear Regulatory Commission (USNRC) in September, 1978. The document summarized the findings of the USNRC regarding the feasibility of the proposed operation and the associated effects on the environment and was based upon:

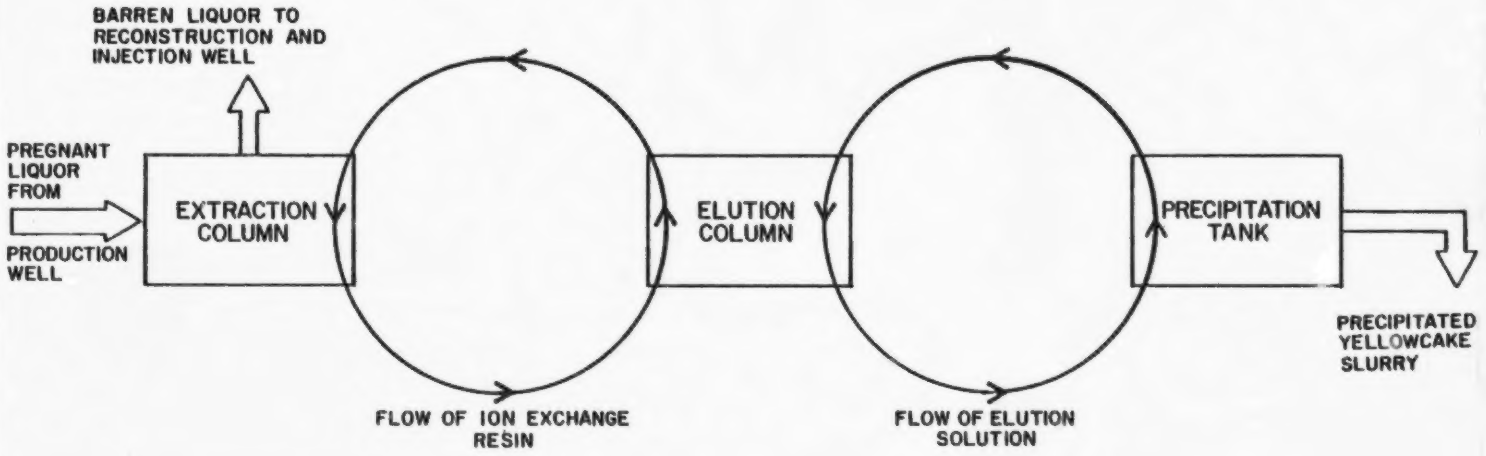

BARREN LIQUOR TO RECONSTRUCTION AND INJECTION WELL
PREGNANT LIQUOR FROM PRODUCTION WELL
EXTRACTION COLUMN
ELUTION COLUMN
PRECIPITATION TANK
PRECIPITATED YELLOWCAKE SLURRY
FLOW OF ION EXCHANGE RESIN
FLOW OF ELUTION SOLUTION

Figure 16. Expected Processing Circuit, Irigaray Mine

1. A Source Material License, dated January 28, 1976;
2. An environmental survey dated January 28, 1976, and supporting correspondence dated May through November, 1976;
3. Responses to questions of the USNRC, dated March 1, 1977;
4. A revised environmental report, of November,1977; and
5. A restoration demonstration in March,1978.

The Environmental Report, as was submitted by Wyoming Mineral Corporation, is required as a supporting document to every application for a Source Material License, to be used by the NRC in assessing potential environmental effects (in accordance with 10 CFR Part 51). The content of the Environmental Report is specified in Regulatory Guide 3.8 of the USNRC.

In addition to the reports and other materials which Wyoming Mineral Corporation had submitted to the USNRC by September 1978, the company was required by the State of Wyoming to obtain the following approvals or permits before starting a commercial, in situ mining operation:

1. License to Mine - issued by DEQ/LQD*
2. Permit to Mine - issued by DEQ/LQD
3. Air Permit to Construct - issued by DEQ/AQD
4. Air Permit to Install Recovery Plant - issued by DEQ/AQD
5. Sanitary Sewage Disposal - issued by DEQ/WQD
6. Potable Water Supply - issued by DEQ/WQD
7. Water Wells - issued by SE
8. Construction of an Impoundment - issued by DEQ/WQD, SE
9. Industrial Siting Permit - issued by Wyoming Office of Industrial Siting
10. Air Permit to Operate - issued by DEQ/AQD
11. Industrial waste disposal site - issued by DEQ/Solid Waste Management Division

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*Abbreviations as follows:

AQD = Air Quality Division
LQD = Land Quality Division
WQD = Water Quality Division
DEQ = Department of Environmental Quality
SE = State Engineer

As of September, 1978, two pilot-scale tests were in operation in the Irigaray Site. The property as described in the report contained 8,540 ha (21,100 acres), of which the initial well field was to occupy 20 has (50 acres). It was anticipated that solution mining would eventually affect about 400 ha (1,000 acres), only part of which was covered under the initial license.

The USNRC summarized salient aspects of the proposed operation as follows:

Groundwater--Groundwater from the Wasatch Formation in the area generally meets drinking water standards, with the exception of one well which produced water containing 0.07 ppm of selenium (the Federal limit is 0.01 ppm and the Wyoming level for livestock consumption is 0.05 ppm). Total dissolved solids (TDS) were generally less than 500 ppm, with Na^+ and SO_4 as the predominant cations. In the mineralized zone, drinking water standards were exceeded by Ra^{226} (radium), gross alpha, and uranium contents; a few hundred feet from the ore zone, however, formation waters generally met the standards.

The main uses of groundwater in the area of the site are livestock watering and private, domestic water supplies. Well tests showed the presence of an artesian head in the aquifer, with a consequent flow toward the northeast. Transmissivities were 53.6 to 58.9 m^2/s (373 to 410 gpd/ft).

Proposed Operation

Expected injection pressures were 340 to 690 kPa (50 to 100 psi), at rates of 0.25 to 0.32 L/s (4 to 5 gpm) per well. The "production cell" was defined as a 7-spot configuration consisting of six injection wells and one production well. All wells were 10.16 cm (4 inch) diameter borings, which were logged, cased, and screened. Production wells contained downhole pumps suspended on a 2.54 cm (1 inch pipe). Restoration was to commence in each completed cell when production had moved 3 cell widths about 73 m (240 feet) away, in order to minimize interference between restoration and mining activities. Estimated feed rates, based on a 230,000 kg/yr (500,000 lb/yr) production rate and an 0.84 L/s (800 gph) injection rate, were shown as in Table 19.

Liquid wastes were expected to consist of solutions of NH_4Cl, carbonates, and other dissolved solids. Total expected volumes of liquid wastes were as shown in Table 20, totalling 25,000 m^3 (20 acre-ft)/yr. The proposed evaporation ponds were designed to evaporate 4,300 m^3 (3.5 acre-ft)/yr; thus, 2.43 ha (6 acres) of evaporation ponds could handle the expected total volume of wastewater. The pond design included impermeable plastic liners and an underlying gravel and pipe collection system.

Prior to reinjection of depleted lixiviant, calcite was to be removed by precipitation. It was believed by the applicant that much of the other dissolved contaminants would co-precipitate with the calcite, producing about 95% removal of Ra^{226}. Vanadium was to be removed by the use of activated charcoal and sulfate by precipitation with barium, should those two dissolved constituents have built up to levels above pilot-scale values.

Table 19. Estimated Feed Rate Ranges for 500,000 lb/yr Production, Irigaray Mine

	lb/hr	Tons/yr
a) Lixiviant for 800 gph injection		
CO_2	75-225	325-985
NH3	40-120	175-525
50% H_2O_2	75-250	325-1100
b) Reagents for 4.5 gpm Eluant Bleed		
NH_2HCO_3	35-100	150-440
NH_4Cl	75-200	325-875
35% HCl	25-70	110-305
NH3	5-20	22-90
c) Fuel		
Propane	20-60	90-260

Table 20. Expected Volumes of Liquid Wastes for a 500,000 lb/yr Production Rate, Irigaray Mine

Overproduction of well field at 1% of design production rate	14.6 acre-ft/yr
Well cleaning to maintain flows	5.5 acre-ft/yr

It was estimated by the NRC that the crystalline concentrates in the evaporation ponds would accumulate assorted ammonium and alkaline earth salts (e.g., NH_4Cl, NH_4SO_4, $RaSO_4$, and $CaCO_3$) at a rate of about 500 tons/yr, all containing radioactive materials.

Solid wastes were to be stored temporarily in lined ponds under liquid seals. A maximum accumulation time of five years was permitted under the license.

Atmospheric emissions were expected to be limited to combustion byproducts and yellowcake fines from the dryer. The latter were expected to total about 45 kg (100 lb)/yr, after passing through a high-intensity venturi scrubber. These losses, equalling approximately 0.15 Ci of U^{238}, equal the natural background value. The USNRC estimated that 1.4 Ci/yr of Rn^{222} (Radon) would be emitted from the evaporation ponds and 76 Ci/yr from the surge tanks.

The recommendations of the USNRC showed concern with: 1) The effectiveness on a production scale of the reverse osmosis treatment, which was in a developmental stage; and 2) the residual NH_3 in the aquifer. The NRC recommended that, until the ammonia problem is resolved, the use of ammonia-based lixiviant by the applicant be limited in volume.

According to the USNRC, unavoidable adverse environmental impacts caused by the operation were:

1) Air emissions - (These were judged to be of negligible magnitude.)

2) Surface water contamination - (Some possible local deterioration was expected.)

3) Groundwater consumption - (An estimated $1.2 \times 10^6 m^3$ would be permanently removed, mostly during restoration operations.)

4) Radioactivity - (Some small increase in the level of local radioactivity was expected.)

The question of the residual ammonia in the aquifer was addressed by the Wyoming Department of Environmental Quality in a letter of August, 1978, in which the Department stated its intention to require the applicant to meet any restoration standards that might be developed in the future, consistent with the state of the art of solution mining in Wyoming. The Department also stated a requirement for sampling of nitrosamines on a quarterly basis.

Operational History

On March 27, 1979, approximately six months after the operation began, an excursion was detected with the use of three shallow monitoring wells. Subsequently, nine exploratory wells were drilled to assess the cause of this problem. Possible causes of this excursion were:

1) Natural hydrologic connections between the shallow aquifer and the deeper, production zone;

2) Interaction between the two aquifers through abandoned and unplugged drill holes;

3) Ineffective cement around one or more well casings; and

4) Loss of casing integrity due to flaws or damage .

In order to assess the cause of the excursion, a program of packer tests and a televiewer examination of the well field was initiated. Packer tests showed that two injection wells in Well Field C were leaking. These injections wells were converted to production wells and overproduction was commenced at several nearby production wells. Pumping of contaminated water from the shallow aquifer was then initiated, through additional shallow wells. In July, a televiewer survey of the wells suspected of having casing damage, as wells as representative wells in Production Units I through IV, was carried out. On July 16, Wyoming Mineral Corporation requested a 30-day extension to the required period for correction of excursions; this extension was granted by DEQ. By August 24, 1979, a correctional trend had been established and maintained in the shallow aquifer, while production operations continued. This trend was the result of:

1) Direct withdrawal of water from the shallow aquifer through two wells at a combined rate of 0.066 to 0.11 L/s (1500 to 2500 gpd); and

2) Indirect withdrawal from the shallow aquifer through pumpage from the production zone through converted injection wells, at a combined rate of 0.123 to 0.438 L/s (2800 to 10,000 gpd).

At that time, cleanup of the shallow aquifer had progressed to the point that the shallow monitor wells that originally had detected the excursion were reported as being off "excursion status."

Analysis of all test data led to the conclusion that casing leaks resulting from well completion and stimulation practices were responsible for the excursion. Pumping from the shallow aquifer reduced rather than increased the level of contamination; therefore, it was inferred that no stratigraphic connection existed between the two aquifers.

On October 29, 1979, Wyoming Mineral Corporation stated its intention to continue the cleanup operation by continuing to pump from the shallow aquifer at maximum capacity through some wells, in order to exaggerate the cone of depression around offending wells. It was also suggested that Cl^- be used as an indicator of excursions for monitoring purposes. At that time chloride levels were reported to be below the limit for drinking water, and V, As, and Se were below the limits of detection.

In June, 1979, Wyoming Minerals Corporation had requested an amendment to its license from the USNRC to allow an increase of leachate flow from 50 to 130 L/s (800 to 200 gpm). This was followed in February, 1980, by a request to the Wyoming DEQ for a permit to change to a non-ammonia type of lixiviant, with a restoration demonstration, and to expand its permitted operating area by 20%. In the same month, plans to mine an alternative lixiviant field using Na, Mg, and Ca bicarbonate as a solvent were submitted to the USNRC, together with a groundwater restoration plan for that field. Restoration was to be accomplished by recycling clean water through the production zone, using an ion-exchange unit.

The area in the shallow aquifer to be cleaned up was defined as being enclosed by the 18 ppm Cl^- isopleth. It was estimated that approximately 37.8 million liters (10 million gallons) of cleanup water would be required to reduce the Cl^- concentration to about 11 ppm. This would involve the exchange of 1 to 1.5 pore volumes at a rate of flow of 1.8 L/s (28 gpm) at the recovery wells, over a period of one year. The installation of forty-eight additional wells in the cleanup zone was also recommended (Wyo. Min. Corp., 3-7-80).

Restoration of the production zone in the initial well field was to begin in May of 1980. This process included soda-lime softening to reduce a carbonate and bicarbonate levels; the addition of $CaCl_2$ to elute NH^+_4; and the use of reverse osmosis to remove residual solubles and trace elements. A water fence was to be used to isolate restoration areas from active mining areas. In accordance with the conditions of the license, a minimum of two wells in the mined zone, two wells in the direction of maximum transmissivity, and two wells on the trend of the orebody were to be monitored at quarterly intervals for one year after completion of the restoration operation. Both of the above plans were approved by the Wyoming DEQ on March 7, 1980.

On March 21, 1980, Wyoming Mineral Corporation was notified by the Wyoming DEQ that an uncontrolled excursion existed at the site, based on their discovery of two consecutive, excessive Cl^- concentrations in Well Field F. (Wyo. DEQ, 3-21-80). Four days later, Wyoming Mineral Corporation requested approval of a plan to remedy this condition. This plan involved a continuation of withdrawal from production wells in the affected area and shutdown of injection wells within a 1-cell radius. In addition, a series of shallow exploration holes around the offending well was proposed to locate the excursion, followed by execution of the cleanup plan already submittted (Wyo. Min. Corp., 3-25-80).

Because restoration had not been accomplished in the ammonia-leach production units to levels of 0.5 ppm or less, the Wyoming DEQ declined to issue a permit to proceed with mining using a non-ammonia lixiviant (Wyo. Min. Corp., 4-16-80). The USNRC then issued an order to Wyoming Mineral Corporation to suspend the operation (USNRC, 1980), because the excursions of March an early April were not attributable to defective well casings, and that hydraulic communication existed between the production zone and the shallow aquifer. The order directed Wyoming Mineral Corporation to cease injection of refortified ammonia lixiviant, to continue to circulate unrefortified (barren) leach liquor, to continue current activities toward the cleanup of the shallow aquifer, and to commence preparations for restoring and decommissioning the site.

On May 23, 1980, the shutdown order was terminated and permission was given to proceed with operations using a sodium lixiviant. Conditions for this permit included 1) monitoring Cl^- around the production zone; 2) drilling additional test wells; 3) conducting pump tests to evaluate hydrogeologic conditions; 4) continuing the cleanup of the shallow aquifer; and 5) carrying out geophysical tests to further define the hydrostratigraphy of the area.

On June 27, 1980, Wyoming Mineral Corporation reported to the USNRC that further excursions had been detected, in Production Unit 5. Chloride and alkalinity values in shallow monitor wells there exceeded baseline values established a month earlier, although Unit 5 was only recycling unfortified lixiviant. Unit 5 was accordingly shut down and pumping begun at the shallow monitor wells. On July 3, an excursion condition was reported in another monitor well, followed on August 12, by still another.

In December, 1980, Wyoming Mineral Corporation was able to report to the Wyoming DEQ that the non-ammonia field had been restored to baseline values, drinking water standards, or Wyoming groundwater standards, and the essentially all heavy metals and radionuclides had been restored to pre-mining conditions. This restoration program involved the exchange of 11.5 pre-volumes at 1.9 to 3.2 L/s (30 to 50 gpm).

6.4 HEAP LEACH FACILITY AT AMBROSIA LAKE, N.M.

Introduction

The United Nuclear Corporation (UNC) operates an experimental heap leach facility for uranium extraction at the Old Phillips Mill in the Ambrosia Lake Mining District, located 40 km (25 miles) north of Grants, New Mexico (Appendix A, 21). This facility uses tailings and low-grade ore from conventional mining and milling operations in the area as feed stock. Water for the process is obtained from underground workings in UNC's Section 27 Mine. The uranium-rich liquor from the heap leach operation is processed in an ion exchange plant which was originally built to extract uranium from the water pumped from the underground mines.

The Ambrosia Lake Mining District lies to the west of Mt. Taylor along a series of southward facing cliffs, mesas, cuestas, and intervening soft rock valleys. It is in a valley three miles wide and seven miles long eroded into the Mancos Shale Elevation is approximately 2,000 m (7,000 feet) above sea level. Physiographically, Ambrosia Lake is on the south rim of the San Juan Basin, east of the Zuni uplift.

The Old Phillips Mill is situated above a 9 to 12 m (30 to 40-foot) thick layer of alluvium that is underlain by the Mancos Shale, the Dakota Sandstone, and the Morrison Formation.

Hydrology

The Westwater Canyon sandstone member of the Morrison Formation is the principal aquifer for the region, as well as the principal ore horizon in the Ambrosia Lake Mining District. Water pumped through the ion exchange plant from the Phillips mine dewatering operation is from this aquifer.

Overlying the Morrison Formation is the Dakota Sandstone which is also a regional aquifer, but wells completed in this horizon are less productive and the water from them is not considered potable. The Mancos Shale overlies the Dakota Sandstone, and was originally reported to be an aquiclude. However, numerous drill holes, ventilation holes, and abandoned mine shafts in the district are of concern as possible routes of vertical migration of water from the overlying alluvium to the underlying Dakota aquifer.

An upward flow gradient exists between the Dakota Sandstone and the Mancos shale. This gradient serves as a hydraulic barrier, but the numerous mine dewatering projects in the Grants region could reverse its direction in the future. Direction of flow in the Dakota aquifer is to the northeast, following the regional dip of the beds.

A shallow aquifer exists in the alluvium overlying the Mancos Shale, approximately 12 m (40 feet) below the surface; the water, however, is of poor quality because of mineralization from the Mancos Shale. Water quality has continued to degrade in this aquifer since the onset of mine dewatering in the 1950's. Direction of flow is towards the northeast, following the topography. Fine silt and clay beds overlie this aquifer and would impede downward movement of any contaminated water from the holding ponds, tailings pile and ion-exchange operation.

Annual rainfall in the Ambrosia Lake area averages 35.13 cm (13.83 inches). A maximum rainfall for a storm was calculated at 51 (20 inches) by UNC for the site. Berms designed to exclude flooding from this storm were constructed around the heap leach pads. Within a 1.6 km (1 mile) radius of the heap leach pads, the only surface waters consist of mine-water holding ponds. Arroyo Del Puerco, to the northeast of the Old Phillips Mill, is an intermittent stream channel. No discharge to this stream will occur as a result of plant operations.

Mine Plant

On July 17, 1980, UNC began to carry out experimental heap leaching of mine tailings at the Ambrosia Lake Old Phillips Mill. Prior to 1971, an ion exchange unit had been installed to extract uranium for water in UNC's Section 27 Mine. The heap leach operation was built as an additional loop within this closed-circuit system.

The plant was designed to operate for less than one year and to provide operational data for possible future commercial-scale, heap leach operations. These data included flow rates to the pile, collection rate below the pile, changes in water quality and the economic feasibility of such an operation. The leaching pad holds 20,200 tons of low-grade ore and tailings; it was originally designed to contain two ore piles but was modified to hold a single pile with two sets of ponds. Feed water from either the mine water pipeline or the ion exchange holdings ponds is applied at a rate of 3.2 L/s (50 gpm) for five hours every 10 days. The uranium content of water leaving the leach pad will be below 500 mg/l. The pad is underlain by 6 mil-thick, polyethylene plastic sheeting, on top of a permaprime sealant sprayed onto the ground.

Leachate from the leach pad is pumped to the ion exchange plant, where the dissolved uranium is removed. The processed water is then returned to the underground mine workings. The pregnant eluant from the ion exchange plant is transported by truck to the UNC-Homestake Partners Mill, where the uranium is precipitated out. The barren solution is then returned by truck to the Old Phillips Mill, where it is re-inserted into the closed circuit between the underground workings and the ion exchange plant.

Three monitoring wells were installed on the north, east, and west sides of the leach pad approximately 6.1 m (20 feet) outside of the berm surrounding the pads. The wells were drilled through the alluvium and 0.9 m (3 feet) into the Mancos Shale, in order to monitor the shallow aquifer. Groundwater in this aquifer would be the first to be affected by contamination from the leach operation. The casing of these wells was perforated along the lower 9.1 m (30 feet). The wells were sampled for molybdenum, selenium, TDS, vanadium, total uranium, and dissloved radium 226 before heap leaching began, and on a quarterly basis thereafter. Results of the baseline sampling and the first quarterly report to NMEID are shown in Table 21.

Table 21. Ambrosia Lake Groundwater

PRE-OPERATIONAL

	May 6, 1980	May 15, 1980	June 18, 1980
Well #1			
Mo	0.007	<0.001	0.014
Se	0.110	0.034	0.024
TDS	4,289.3	4,314.4	4,705.8
V	0.007	<0.001	0.009
U	0.16	0.13	0.15
*Ra^{226}	1.8	1.9	3.1
Well #2			
Mo	0.006	<0.001	0.022
Se	0.124	0.033	0.024
TDS	2,886.3	2,985.2	3,379.3
V	0.007	<0.001	0.013
U	0.10	0.11	0.09
*Ra^{226}	2.8	1.7	4.4
Well #3			
Mo	0.003	<0.001	0.014
Se	0.121	0.0817	0.044
TDS	4,189.0	3,786.0	3,944.0
V	0.010	<0.001	0.016
U	0.05	0.04	0.04
*Ra^{226}	0.7	0.9	1.8

OPERATIONAL

	Aug. 3, 1980	Nov. 4, 1980
Well #1		
Mo	0.10	0.003
Se	0.008	0.016
TDS	5,413.3	5,561.5
V	0.016	0.018
U	0.12	0.12
*Ra^{226}	7.16	4.63
Well #2		
Mo	0.015	0.006
Se	0.024	0.039
TDS	4,092.3	3,750.3
V	0.015	0.014
U	0.04	0.07
*Ra^{226}	1.88	2.26
Well #3		
Mo	0.007	0.005
Se	0.042	0.055
TDS	4,320.2	4,102.5
V	0.016	0.019
U	0.04	0.05
*Ra^{226}	1.56	1.83

All parameters reported in mg/L except those indicated as * (pCi/L).

Upon completion of the experimental heap leaching operation, residual materials on the pads and the polyethylene liner will be sent to the UNC Church Rock Mill and combined with their present tailings pile.

As of February, 1981, no problems of environmental contamination had developed at the plant (as a result of the operation of the heap leach and ion exchange).

6.5 THE HIGHLAND MINE, CONVERSE COUNTY, WYOMING

Introduction

This commercial-scale operation is carried on by the Exxon Minerals Company in Converse County at the south edge of the Powder River Basin, some 32 km (20 miles) northwest of the town of Douglas (Figure 14). Uranium is produced from sandstone ore in the Fort Union Formation, of Paleocene age. The production zone is overlain and underlain by shale formations some 4.6 m (15 feet) thick. Drinking water is produced from an aquifer located about 46 m (150 ft) above the ore-bearing unit, supplying 3 wells within 3.2 km (2 miles) of the site. Several sandstone and shale units lie between the production zone and this aquifer.

Proposed Operation

In September, 1970, Humble Oil and Refining Company applied for a Source Material License from the U.S. Nuclear Regulatory Commission, proposing to carry out pilot testing at the site. Pump tests to prove pressure communication between injection and production wells in a 7-spot pattern (one injection well, six production wells) were carried out. Tracer studies, using a saline solution of 250 mg/L NaCl, were carried out to confirm the hydraulic properties of the formation. It was proposed that sodium carbonate-bicarbonate lixiviant, using oxygen as an odixizer, would be injected at a rate of 7,938 to 15,876 liters (50 to 100 barrels per day for a total volume of 6,032 million liters (38,000 barrels or 1,596,000 gals). Production wells then would be started and a balance would be established to cycle approximately 20 million liters (128,000 barrels or 5,376,000 gals) of lixiviant through the ore zone. The pregnant liquor was to be processed in an ion-exchange plant, which would leave approximately 60 ppm of dissolved uranium in the liquor. Elution of the ion-exchange columns was to be accomplished using ammonium nitrate and nitric acid.

Wastes were to be discharged into an evaporation pit. Solid wastes were to be buried and seeded at the end of the operation. No airborne particulate contamination was expected because all processing was to be done with wet materials. The precipitated yellowcake was to be packaged while still wet enough to prevent dust generation.

Restoration was to be accomplished by pumping all lixiviant from the formation, removing introduced materials, and pumping water to a tailings pond. It was expected that approximately 8.3 million liters (52,000 barrels or 2,184,000 gals) of clean water would be required to remove essentially all of the leach solution.

Expected environmental impacts were:

1) Removal of approximately 12.7 million liters (80,000 barrels or 3,360,000 gals) of groundwater

2) Residual traces of carbonate-bicarbonate solution in the formation; and

3) Creation of evaporated residues in surface pits.

No long-term, adverse effects were foreseen. An operating license was issued by the USNRC in November, 1970.

The pilot well pattern was a symmetrical spacing of the six production wells on 27 m (90-ft) radii around the injection well. In addition six minitor wells were placed on 46 m (150-ft) radii from the center well. Results of analysis of water pumped from the ore are shown in Table 22.

Table 22. Analysis of Water from Ore Zone--Highland Mine*

Na	161 ppm	HCO_3	237 ppm
Ca	77 ppm	Se	<0.5 ppm
Mg	13 ppm	U	212 ppm
Cl	27 ppm	Ra^{226}	12×10^{-8} uc/ml
So_4	119 ppm	Th^{230}	8.6×10^{-8} uc/ml

* Based on an average of 3 samples from production wells.

On January 1, 1973, the license was amended to reflect the merger of Humble Oil with the Exxon Corporation.

Operational History

Operations in the initial pilot plant production area were carried on from March, 1972, to November, 1974. During that period, 38.74 million liters (10,248,000 gals) of lixiviant were injection through the production well, with 38.90 million liters (10,290,000 gals) being produced. After injection was stopped, 78.38 million liters (21,000,000 gals) were pumped from all 7 wells.

Monitoring efforts emphasized the detection of increases in uranium content of water in the six monitoring wells. Detectable changes were observed in mid-1973 and mid-1974; each time, the excursion was controlled by adjusting injection and production rates to pull the leach liquor plume back into the production zone. Arrival times of the plume at the monitoring wells were earlier than had been anticipated, due to the presence of stratigraphic non-uniformities in the ore-bearing beds.

After cessation of injection in November, 1974, uranium concentrations in observation wells decreased, passing the limit of detectability by June, 1975. By that time, Exxon reported that carbonate and bicarbonate ion were essentially at baseline levels, and that trace metals, with the exception of arsenic and selenium, were not mobilized in sufficient amounts to be of concern to groundwater quality. During the pilot operation, concentrations of radon daughter products occasionally exceeded acceptable levels. New filters and blower systems were installed to overcome that problem.

In October, 1977, Exxon applied for a permit to drill a new test pattern of four injection wells, ten production wells, nine observation wells, and two monitor wells. The monitor wells were to be located in the middle of this double-5 spot pattern and were completed above and below the production zone aquifer. At that time, pumping from the initial production area continued, at a rate of about 0.95 L/s (15 gpm). Baseline samples obtained from this pattern of wells produced the results shown in Table 23. A license to operate the second pilot area was issued in May, 1978.

In March, 1979, Exxon reported that bicarbonate values in some observation wells exceeded the control limits by small amounts; also, in two wells, conductivity values were high. Exxon did not believe that this was due to a leach-liquor excursion. By mid-April, 1979, Exxon reported that a new observation well had been drilled between the ore zone and the wells showing high bicarbonate values. Samples from this well did not have similar concentrations of bicarbonate, and this demonstrated that a plume of leach liquor did not extend between the two areas.

In December, 1979, a minor casing leak was discovered in an injection well. This was the result of a pressure test, using down-hole packers. The leak was determined to be adjacent to an aquifer lying above the production zone. To determine the extent of any excursion, an additional observation well was drilled 3 m (10 ft) from the leaky injection well, and water samples were obtained from this aquifer. Comparison of analytical data with baseline values showed that an excursion had occurred through the leaky casing. Pumping was begun through the new well, resulting in a significant decline of initially excessive concentrations of excursion parameters after 96 hours. By March, 1980, the clean-up of this excursion was completed.

Exxon conducted a downhole television survey of the leaky well, and determined that the leak was the result of hairline cracks and a bad joint in the PVC tubing. Exxon indicated that they would not longer use PVC tubing in their wells, but would instead utilize fiberglass or steel pipe.

As of November, 1980, no further excursions or environmental problems had been reported at the mine.

Table 23. Analysis of Water--Pilot Plant Area, Highland Mine

	Wyoming DEQ[1] Guideline No. 4	Sample Well #13	Pilot Well #6	Pilot Well #3	Obsev Well #7	Obsev Well #9	Control[4] Well In Ore Zone	Control[5] Well Outside Ore Zone
Date of Sample		2/1/77 2/15/77[3]	4/21/77	4/21/77	4/21/77	4/21/77	2/1/77 2/2/77[3]	2/14/77 2/15/77
Aluminum-mg/l	0.5	.46	.049	.03	.13	.17	.009	.123
Arsenic-mg/l	0.2	.30	.15	.065	.023	.014	.0015	<.001
Boron-mg/l	5.0	.1	.1	.1	<.1	.1	0.2	.2
Cadmium-mg/l	0.05	<.001	<.001	.001	<.001	.005	.002	.001
Chromium-mg/l	1.0	.002	.002	.004	.010	.003	<.001	.0345
Copper-mg/l	0.5	.016	.13	.004	.019	.069	<.001	<.001
Fluoride-mg/l	2.0	1.15	0.6	0.3	0.7	0.2	0.2	0.25
Lead-mg/l	0.1	.005	.013	.002	.037	.16	.002	.010
Mercury-mg/l	0.01	.0003	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Selenium-mg/l	0.05	.145	.30	.003	.004	<.001	<.001	.001
Zinc-mg/l	25	.010	.020	.029	15	16	.007	.016
Sulfate-mg/l	3000	189[6]	152	156	136	114	141[6]	132[6]
Chloride-mg/l	2000	18	9	12	27	10	6	17
Radium-^{226} pCi/l	30[2]	200	92	500	125	4.9	470	3.3
Thorium-^{230} pCi/l	2000[2]	160	113	48	230	3.8	0.55	0.2
Uranium-mg/l	44.3[2]	78	15	4.1	3.4	.15	.095	.045

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[1] Wyoming Department of Environmental Quality, Division of Land Quality Guideline No. 4 (revised) November 9, 1976. Part II: Water Quality Criteria for Wildlife and Livestock Impoundments.

[2] MPC above background for release to an unrestricted area, 10 CFR 20, Appendix B, Table II.

[3] Average of two samples.

[4] Located 700 feet east of pilot injection well in the same sand.

[5] Located 1100 feet southeast of pilot injection well in the same sand.

[6] All sulphur calculated as $SO_4^=$.

Analyses are by mass spectrometry except for Ra-^{226} and Th-^{230}.

Reference: Exxon Minerals Co., 1978.

SECTION 7

PAST AND CURRENT RESEARCH

This section presents brief summaries of past and ongoing research projects that address the environmental effects from unconventional extraction of uranium and the technologies to mitigate such effects. A primary source of information that was used in compiling this list was two computer searches of the Smithsonian Scientific Information Exchange (SSIE) data base, which maintains "notices of research projects." Because it is not always possible to determine project completion dates, several of the projects that are identified as current research may have been completed and the results published. Another major source of information is a U.S. Bureau of Mines (1980) publication that lists minerals environmental research for FY 1980. A similar report for FY 1981 will be available after April 20, 1981, from the Division of Minerals Environmental Technology. Information regarding all other research projects was obtained from proceedings of symposia and from other published literature. These project summaries are provided below.

Effect of Sodium Silicate on Leaching Uranium Ores with Hydrogen Peroxide

Laboratory experiments demonstrate that additions of small amounts of sodium silicate to hydrogen peroxide (H_2O_2) leaching solutions prevents the loss of permeability. With some ores, it also helps stabilize H_2O_2 against decomposition. This research project was conducted by E.I. duPont de Nemours and Co., Inc., Chemicals, Dyes and Pigments Department, Wilmington, Delaware (Lawes, 1978).

Environmental Assessment of In Situ Mining

This study evaluates selected environmental effects of in situ leaching and hydraulic borehole mining of uranium, copper, and phosphate ores. The study specifically discusses the impacts associated with in situ uraniun leaching in Texas and Wyoming. For each of the in situ processes and ores investigated, the physical and chemical characteristics of the systems are described, the toxicity of the leaching solutions are presented, and the potential environmental effects are discussed. The assessment was conducted by PRC Toups under a Bureau of Mines contract, which was administered under the direction of the Twin Cities Research Center, Minnesota. The final report was published December, 1979 (Kasper, et al., 1979).

Geochemical Changes During In Situ Uranium Leaching with Acid

The Bureau of Mines measured the geochemical changes as sulfuric acid was used for in situ uranium leaching by Rocky Mountain Energy Company near Casper, Wyoming. Cores and groundwater were analyzed before leaching. Water samples were taken from observation wells located between injection and production wells as the leach solution was brought up to full strength in several steps. Measurements were made of pH, Eh, temperature conductivity, total dissolved solids, dissolved oxygen, HCO_3, U, V, Na, K, Ca, Mg, SO_4, Cl, Mo, Mn, Fe, Al, Si, F, P, As, and Se. The data were gathered to assist in geochemical modeling of leaching and to study the potential environmental effects of acid leaching. Environmental considerations appear favorable. For example, the concentration of Se, a toxic element often found in uranium deposits, stayed below the EPA standard for drinking water (Tweeton, et al., 1979).

Ground Water Restoration for In Situ Solution Mining of Uranium

This paper, a summary of a study funded by the Bureau of Mines, reviews the state of the art in restoring groundwater quality after in situ uranium leaching. Current restoration practices discussed include disposing of liquid wastes in deep disposal wells and evaporation ponds, producing from all wells during restoration, and recirculating water purified in surface plants. Methods for predicting the effectiveness and cost of current techniques are presented. Possible alternative techniques are also described. Two restoration operations are discussed (Riding, et al., 1979).

The Push-Pull Test: A Method of Evaluating Formation Adsorption Parameters for Predicting the Environmental Effects of In Situ Coal Gasification and Uranium Recovery

The push-pull test, which is a simple injection and pumping sequence of groundwater spiked with solutes of interest, is presented as a method of determining the adsorption characteristics of a formation. Adsorption properties are necesary to predict restoration from both in situ coal gasification and in situ uranium extraction. Two field push-pull tests were conducted on uranium formations in Wyoming. Adsorption properties estimated from these tests on the basis of a simple cell model were compared to the laboratory values. In the first case, excellent agreement was observed between the values estimated from the field test and the values measured in the laboratory. In the second case, the value for k_d determined in the laboratory was five times higher than the field value. It was concluded the the push-pull test is a viable technique for comparing laboratory to field adsorption values (Drever and McKee, 1979).

Analysis of Groundwater Criteria and Recent Restoration Attempts

The objectives of this work effort are to present, compile, and compare the criteria for groundwater quality restoration and the effectiveness and costs of the methods used, to develop empirical expressions for predicting the amount of aquifer flushing that is required, and to improve predictions for the costs of restoration. This is an ongoing effort by Resource Engineering and Development, Inc. (U.S. Bureau of Mines, 1980).

Assessment of Leachate Movement from Ponded Uranium Mill Tailings

This research project was designed to determine the interaction of tailings leachate with clay liner material and subsurface sediments that are representative of the Morton Ranch site. Using obtained interaction data, numerical models then were to be used to describe and predict the groundwater leachate movement beneath the tailings pond. The project was scheduled to be completed by early 1980. The project was supported by the U.S. Nuclear Regulatory Commission and was conducted by Battelle Memorial Institute in Columbus, Ohio. The project sponsor was R.J. Serne of the Pacific Northwest Laboratory (SSIE, 1980).

Biochemistry of Uranium Mill Wastes

Studies in the southwestern U.S. are being conducted by personnel at the Los Alamos Scientific Laboratory (DOE) to evaluate the transport and environmental fate of contaminants associated with uranium mill tailings and to investigate methods of containment of these waste materials. Contaminants of interest include Se, Mo, As, V, U, and Ra^{226}. Field studies at inactive tailing piles have included groundwater quality monitoring, measurement of radon-222 flux, investigation of contaminant uptake by vegetation, and stabilization of sites by establishing native vegetation. The primary investigator on this project is D.R. Dreeson. (SSIE, 1980).

Cleanup and Recycle Technology for Mine and Mill Waters

The objective of this project is to devise process-water treatments that permit water reuse or safe discharge and recovery of minerals and metals contained in the waters. Work will include the removal of heavy metals from ammoniacal process solutions used in permit fertilizer production; removal of selenium from uranium mine wastewater in Ambrosia Lake, New Mexico; and recovery of molybdenum catalyst preparation wastewater. (U.S. Bureau of Mines, 1980).

Computer Simulation of Chemical Concentrations During In Situ Leaching

A solute transport model is to be developed using the ISL-50 hydrology model and a simulation of leaching chemistry kinetics. Use of the model would enable site operators to predict recovery rates for in situ leaching of copper and uranium and to assist in the optimal selection of well locations, pumping rates, and leachant and oxidant concentrations. Project completion was scheduled for the end of FY 79. This project was performed by the Bureau of Mines, Twin Cities Metallurgy Research Center, Minnesota. Project contact is R.D. Schmidt (SSIE, 1980).

Contamination of Ground and Surface Waters by Uranium Mining and Milling

This project will involve work efforts to measure rate of pollutant migrations from uranium mining and milling operations, to develop improved techniques for describing these migrations and predicting their rates, to determine if algae and bacteria can be used to lower pollutant concentrations and hence, to reduce water pollution. This effort is through the University of Colorado (U.S. Bureau of Mines, 1980).

Detection of Lixiviant Excursions with Geophysical Resistance Measurements During In Situ Uranium Mining

Westinghouse Electric Corp. of Annapolis, Maryland, is planning to develop, test, and demonstrate a commercially acceptable resistance measuring system. The system would detect the excursion of a lixiviant, with a resistivity of about half of the groundwater it displaces, before it reaches a monitoring well at a depth of 120 m (400 feet). This work is sponsored by the Bureau of Mines, Twin Cities Mining Research Center, Minnesota (SSIE, 1980).

Development of Field-Demonstration of Environmentally Attractive Leachants

Project objectives are to determine whether sodium carbonate or potassium carbonate, with or without clay-encapsulating additives, can be substituted for ammonium carbonate as a leachant without excessive cost or loss or permeability, and to determine the optimum strengths of these leachants for extracting uranium from several types of sandstone ores. This is an ongoing effort by the University of Texas. In a new follow-up project, the techniques that are developed will be field-demonstrated (U.S. Bureau of Mines, 1980).

Development of In Situ Leaching Technology for Uranium

The objective of this project is to improve the following processes for in situ uranium leaching: the construction of injection wells, the selection of lixiviants, and the restoration of groundwater quality after leaching. The Bureau of Mines, Twin Cities Metallurgy Research Center, is performing the research (SSIE, 1980).

Environmental Aspects of Uranium Mining in Minesota

During this project, the possible environmental problems will be defined, baseline environmental monitoring programs will be developed, and environmental effects research will be initiated. This project will involve work with the State, landowners, and potential mining companies. This is an ongoing project (U.S. Bureau of Mines, 1980).

Evaluation of Best Management Practice for Mining Solid Waste Storage, Disposal, and Treatment

The objective of this program is to extensively monitor ground and surface water and air quality at approximately eight waste disposal sites including metallic ores, phosphates, and uranium. In order to comply with sections 3004 and 4004 of the Resource Conservation and Recovery Act, EPA is sponsoring this study with the Bureau of Mines cooperation. EPA will use the results of this study in their development of standards for "Best Management Practice" for disposal of metallic ores, phosphate, and uranium wastes. This is an Interagency Agreement with EPA, and contract to PEDCo (U.S. Bureau of Mines, 1980).

Evaluation of Lixiviation of Mine Wastes

The purpose of this project is to determine which types of, and to what extent, mineral wastes contaminate groundwater through leaching of acid-forming or toxic-forming materials. This is an ongoing effort by Calspan Corp. (U.S. Bureau of Mines, 1980).

Geochemistry of Uranium Leaching

This project involves a study of the processes that are involved in the leaching of uranium ores. The studies concentrate on the interactions between the host rock and leaching agents. Empirical and theoretical models of the interactions are to be developed so as to enable operators to minimize their impact on the environment. The principal investigator is R.W. Potter, of the U.S. Geological Survey (USGS), Geologic Division (SSIE, 1980).

Hydrochemical Controls on the Migration of Radionuclides from Uranium Mill Tailings

As of FY 79, research was being conducted to characterize the physical, chemical, and mineralogic nature of uranium mill tailings, to determine the mobility of radium associated with the tailings, and to examine the hydrogeochemical controls on the groundwater transport of radium. Parts of this research project involved core sampling of tailings piles, analysis of tailings, examination of radium leaching behavior and distribution, radium transport modeling, and literature review. E.R. Landa is the principal investigator and is with USGS, Water Resources Division, Reston, Virginia (SSIE, 1980).

Hydrologic Impact of In Situ Mining, Weld County, Colorado

The objective of this project is to develop a non-conservative solute transport model that is capable of simulating the in situ solution mining of uranium. The model would be used to determine the hydrologic impacts of the Wyoming Minerals Corporations's in situ mining activities on the groundwater resources in that mining area. Subtasks include: termination of aquifer hydraulic properties and regional groundwater flow patterns, monitoring of an installed observation well for chemical leachate, adaption of the Intercomp Model to simulate the leachate distribution with time, and model verification. As of FY 1979, this program was being conducted USGS, Water Resources Division, Lakewood, Colorado. J.W. Warner is the project contact (SSIE, 1980).

In Situ Leaching Studies on Uranium Ores

The objectives of this study were to develop a technique for the laboratory simulation of in situ uranium leaching and to determine the effects of leaching variables on the permeability and uranium extraction from ores found in Texas and Wyoming. The project was to have been completed by late 1978 by Westinghouse Electric Corp., Pittsburgh, Pennsylvania, and was supported by the Bureau of Mines, Salt Lake City, UTAH (SSIE, 1980).

In Situ Uranium Leach Mining: Consideration of Monitor Well Systems

David L. Durler of United States Steel Corp., and Arthor L. Bishop of Uranium Resources Inc., discuss the importance of certain geologic factors that can influence the groundwater regime and, hence, can affect the adequacy of groundwater monitoring programs. Case histories of three in situ projects are presented (Durler and Bishop, 1980).

New Mexico's First Uranium In Situ Solution Extraction Project

Mobil Oil Corporation began operation of a pilot plant in November, 1979 in northwestern New Mexico. the 3-year pilot test program is intended to determine the technical feasibility, environmental impact, and economics of the operation prior to expansion into commercial production. Initial data indicate that the leach front behavior has been acceptable and that there has been no increase in radon-222 levels at the pilot plant site. No data were available on product shipment or aquifer restoration because neither of these project phases had begun, as of September, 1980 (Coleman and Stewart, 1980).

Operating Experience in the Recovery of Uranium at the Pawnee and Zamzow Sites

Intercontinental Energy Corporation (IEC) is recovering uranium by in situ leaching at the Zamzow site and has completed its production at the Pawnee site; both sites are in South Texas. The authors, Velu Annamalai of IEC and Francis X. McGravey of Ionac Chemical Co. (1980), discuss the solution mining methods that have been used and the problems related to the ion exchange process. The Pawnee site restoration program methods for handling wastes, and approaches to the control of groundwater contamination also are discussed. Additionally, Zamzow plant practices and economics are outlined and process modifications are suggested.

Radiation Dose Models Application to Uranium Solution Mining

Models to estimate radiation exposure from nuclear facilities are to be adjusted to determine the doses that might arise from uranium solution mining, waste spills, and waste storage facility leaks. Using potential theory for fluid flow under a gravity head, the flow to drinking water and irrigation reservoirs can be estimated. This was to be a FY 77 research project conducted by Professor T.A. Parish and C.W. Bishop of the University of Texas, Department of Mechanical Engineering, Austin, Texas (SSIE, 1980).

Research Within the Coordinated Program on Bacteria Leaching of Uranium Ores

Part of this FY 1977 project included an evaluation of the effectiveness of biocide applications in order to prevent bacterial activity in dumps that contain uranium waste material. Delaying the biochemical processes, which intensifies uranium leaching from waste piles, should mitigate adverse environmental effects. This project was conducted by the Rudarski Institute in Yugoslavia (SSIE, 1980).

Restoration of Groundwater Quality After In Situ Uranium Leaching

The purposes of this project were to evaluate existing methods of restoring groundwater quality after in situ uranium leaching, to evaluate alternative methods, to rank the methods according to their effectiveness, and to identify technological deficiencies in the state of the art. Information sources were to include published literature, contacts with leaching companies, and the project staff experience in water treatment. The project was to have been completed during FY 1977 by the Bureau of Mines, Twin Cities Mining Research Center, Minnesota, under the direction of D.R. Tweeton (SSIE, 1980).

Restoration of Groundwater Quality Following Pilot-Scale Acidic In Situ Uranium Leaching at Nine-Mile Lake Site Near Casper, Wyoming

Engelman, et al. (1980) report on the methods used and the results of the 9-month restoration program that began in November 1978. The project was conducted under a cooperative agreement between the Bureau of Mines and a joint venture consisting of Rocky Mountain Energy, Halliburton, and Mono Power Co. About 25 water quality parameters were monitored. pH returned to the preleached baseline at the slowest rate; nearly all others returned within 6 months. Restoration of the Nine-Mile Lake site was considered successful, which should add to the viability of sulfuric acid as an alternative leachant for uranium contained in low-calcium carbonate ores. The acid leachant also sidesteps many of the environmental problems associated with some alkaline leachants.

Environmental Assessment of Fuel Cycle Facilities

The objective of this project is for Oak Ridge National Laboratory to provide technical assistance to the NRC in the preparation of detailed assessments of the environmental impacts associated with or potentially associated with existing or proposed fuel cycle facilties. Included in such facilities may be in situ uranium solution mines and above-ground uranium leaching operations, as well as uranium mills, ore buying stations, and fuel fabrication facilities. H.E. Zittel and M.J. Kelley are the principal investigators (SSIE, 1981).

Evalution of Mass Transport Models for Groundwater Systems

The purpose of this program is to evaluate and develop reliable models that can predict changes in groundwater quality due to the transport and dispersion of dissolved chemical constituents. Models are developed or applied to a variety of problems or areas. One city research plan is the analysis of in situ uranium leaching or of heavy metal transport from mining waste dumps or tailings ponds. The principal investigator is L.F. Konikow, who is with the USGS, Water Resources Division, Denver, Colorado (SSIE, 1981).

Extraction of Radionuclides from Low-Grade Ores and Mill Tailings

The objectives of this program are to investigate the removal, by leaching, of radium-226 and thorium-230 from uranium mill tailings and ores; and to derive solvent extraction methods for the recovery of radionuclides from the leach liquors in a form that is easily handled and disposed. The New Mexico Institute of Mining and Technology, Socorro, New Mexico, is conducting the research for the Office of Surface Mining Reclamation and Enforcement. The project contact is A.E. Torma (SSIE, 1981).

Groundwater Management

New computer models will be developed or existing models will be modified to predict the movement of groundwater and its pollutants. One aspect of this project will involve the use of models in the study of uranium solution mining. Artificial groundwater recharge techniques and pollution from sanitary landfills also will be studied. The Colorado State government is sponsoring the work effort that is being performed by Colorado State University, Fort Collins, Colorado. R.A. Longenbaugh and D.K. Sunada are responsible for this project. (SSIE, 1981).

In Situ Uranium Mining

Various energy companies are planning to test the feasibility of uranium solution mining on the Long Pines Area of eastern Montana. This study will monitor the ecosystem effects of solution mining techniques and wildlife populations and will develop guidelines for reducing these conflicts. Studies will be conducted to furnish the baseline data needed to monitor the effects of solution mining. Long Pines will be used as a model demonstration site for researching the compatibility of wildlife, vegetation, and solution mining. The project will also review Montana's environmental protection statutes in terms of protection of the environment. The U.S. Fish and Wildlife Service, Fort Collins, Colorado, is the sponsoring organization. The research will be conducted by the Montana Department of Fish and Game, in Helena. R. Martinka is the principal investigator (SSIE, 1981).

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APPENDIX A

URANIUM MINING AREAS IN THE UNITED STATES

In this chapter, areas of uranium mining in the United States are identified. Figure 17 shows the areas reporting uranium production through 1979. The largest proportion of production has come from Wyoming, western South Dakota and the Colorado Plateau regions of Utah, Colorado, New Mexico, and Arizona. Texas has assumed an increased proportion of the production in recent years.

Within the United States the known uranium reserves and reliably delineated resources are sandstone ores, magmatic-hydrothermal vein systems, and vein or breccia deposits in sedimentary rocks. The sandstone ores constitute the greatest proportion of the known U.S. reserve.

A.1 TYPES OF MINEABLE URANIUM DEPOSITS

Sandstone Deposits

It is estimated that 90% of the proven uranium in the United States occurs in sandstone ores. The bulk of this reserve and all of the active mines of this type located in the western Cordillera and on the Texas Gulf Coast.

The two types of uranium deposits found in sandstone are differentiated by their geometric and morphologic relationships to the enclosing host rocks. These two types are known as roll front and tabular deposits. Often the actual deposit is a gradation between the two.

Roll front deposits--Typical roll front deposits are peneconcordant to bedding, display sharp contacts between ore and gangue, and are curvilinear in cross section. Localization of the ores is controlled by the oxidation-reduction (redox) boundary. The roll front cuts across sandstone bedding, and the ore deposit is situated on the downdip (unoxidized) side of the boundary (Figure 18). The host sandstone is commonly overlain and underlain by unoxidized, less-permeable sediments.

The grade of this type of deposit averages 0.2 to 3.0% U_3O_8, decreasing with increasing distance from the redox boundary. In plan, ore bodies are sinuous, reflecting the geometry of the channel-fill sandstone host rock. Although the sand might extend laterally for many miles, the metal deposits are not necessarily present along the entire redox boundary.

Carnotite, uraninite, and coffinite are the most abundant uranium-bearing ores. Individual deposits range in size from small pods containing a few tons of ore to large deposits of several million tons. In general, however, ore deposits are small, with lengths and widths rarely exceeding 305 m (1,000 feet).

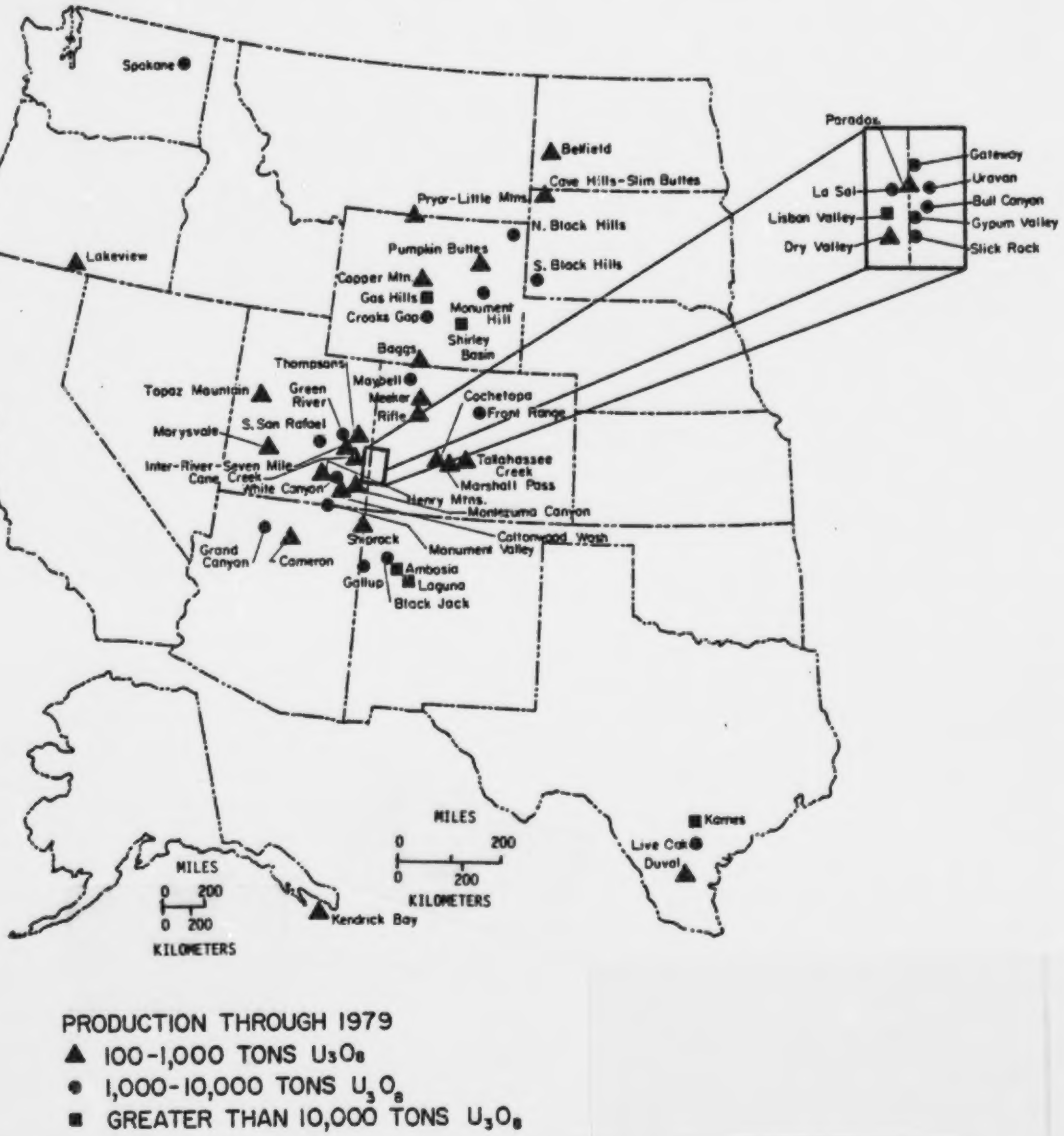
Spokane
Belfield
Cave Hills-Slim Buttes
Pryor-Little Mtns.
N. Black Hills
Pumpkin Buttes
S. Black Hills
Lakeview
Copper Mtn.
Gas Hills
Crooks Gap
Monument Hill
Shirley Basin
Baggs
Thompsons
Maybell
Meeker
Rifle
Topaz Mountain
Green River
Cochetopa
Front Range
S. San Rafael
Marysvale
Inter-River-Seven Mile
Cane Creek
White Canyon
Tallahassee Creek
Marshall Pass
Henry Mtns.
Montezuma Canyon
Cottonwood Wash
Shiprock
Monument Valley
Grand Canyon
Cameron
Gallup
Ambosia
Laguna
Black Jack
Paradox
Gateway
Uravan
La Sal
Bull Canyon
Lisbon Valley
Gypsum Valley
Dry Valley
Slick Rock
Karnes
Live Oak
Duval
Kendrick Bay
MILES
0
200
KILOMETERS
PRODUCTION THROUGH 1979
▲ 100-1,000 TONS U_3O_8
● 1,000-10,000 TONS U_3O_8
■ GREATER THAN 10,000 TONS U_3O_8

Figure 17. Uranium-Producing Areas of the United States
(U.S. DOE, 1980)

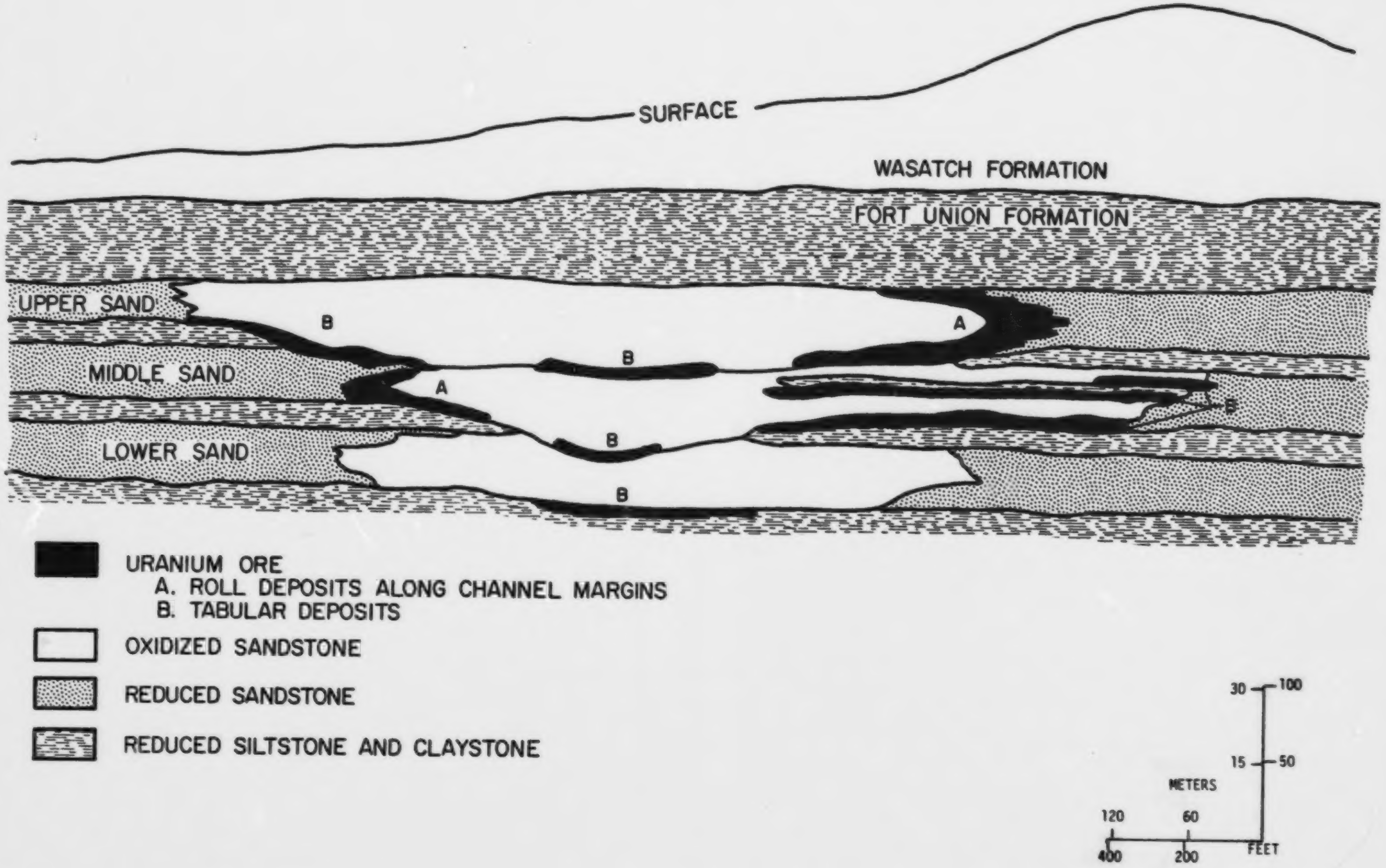
SURFACE
WASATCH FORMATION
FORT UNION FORMATION
UPPER SAND
MIDDLE SAND
LOWER SAND
A
B
URANIUM ORE
A. ROLL DEPOSITS ALONG CHANNEL MARGINS
B. TABULAR DEPOSITS
OXIDIZED SANDSTONE
REDUCED SANDSTONE
REDUCED SILTSTONE AND CLAYSTONE
METERS
FEET
30
15
100
50
120
60
400
200

Figure 18. Typical Roll Front and Tabular Uranium Ore Deposits
(Langen and Kidwell, 1971)

Roll front deposits have no recognizable spatial relationship to igneous-hydrothermal or tectonic activity. The uranium contained in them is thought to have originated from the weathering of volcanic rocks. Groundwater carried the oxidized, dissolved hexavalent uranium down gradient to reducing environments where it was deposited. Reducing environments seem to have formed where carbonaceous material was abundant. Many roll front ores appear to be the result of the remobilization by groundwater of previously deposited ores.

Tabular deposits--Tabular uranium deposits are conformable with the bedding of the host sandstone and are generally oriented subparallel to the strike of the host rock (Figure 18). Grain size of the sandstone host varies from coarse, where tabular deposits occur in paleochannels, to fine in crevasse-splay paleoenvironments. Sorting is usually poorer in tabular sandstone hosts. Tabular deposits occur in locally reduced environments in otherwise oxidized sandstone and, unlike roll front deposits, show little evidence of remobilization. Typically, tabular deposits contain a higher ratio of vanadium to uranium, a lower than average uranium grade and a larger areal extent than roll front deposits. Uraninite and coffinite are the dominant ore minerals, wtih little carnotite. Area often exceeds 305 m (1,000 feet).

The mechanism of formation for tabular deposits is thought to be similar to that for roll fronts. However, evidence for secondary remobilization is absent. Among the explanations offered for the apparent lack of remobilization are low permeability of the poorly sorted, tabular host sandstone and the ability of the vanadium to fix uranium in relatively stable uranyl vanadate compounds.

Most uranium in the United States comes from sandstone deposits in Wyoming, Texas, and the Colorado Plateau region. The deposits of these regions are discussed below.

Deposits in the Wyoming Basin--

Figure 19 shows the major uranium mining areas of the Wyoming Basin. Most of these areas are within the state of Wyoming, but a portion of the Poison Basin and the entire Maybell District are in northwest Colorado.

The Wyoming Basin formed during the Cretaceous Period. Later, uplift along the margins of the basins in the lower Tertiary Period resulted in the deposition of thick sequences of terrestrial clastic sediments that were subsequently buried and later exhumed during the upper Tertiary period. After deposition of these beds, uranium was leached from outcropping granites and volcanic rocks, transported in solution by groundwater, and deposited in the permeable sandstones of the basin.

The Wasatch, Wind River and Battle Spring Formations of early Eocene age and the Fort Union Formation of Paleocene age contain most of the known reserves. The deposits occur in fluvial carbonaceous sandstones in the Crooks Gap, Gas Hills, Southern Powder River, Great Divide and Shirley Basins. They are typical roll front deposits with uranium concentrated along the redox boundary. Tongues of altered sandstone characterized by the presence of hematite, and an alteration envelope of siderite, sulfur, and ferrosalite extend downdip into unaltered,

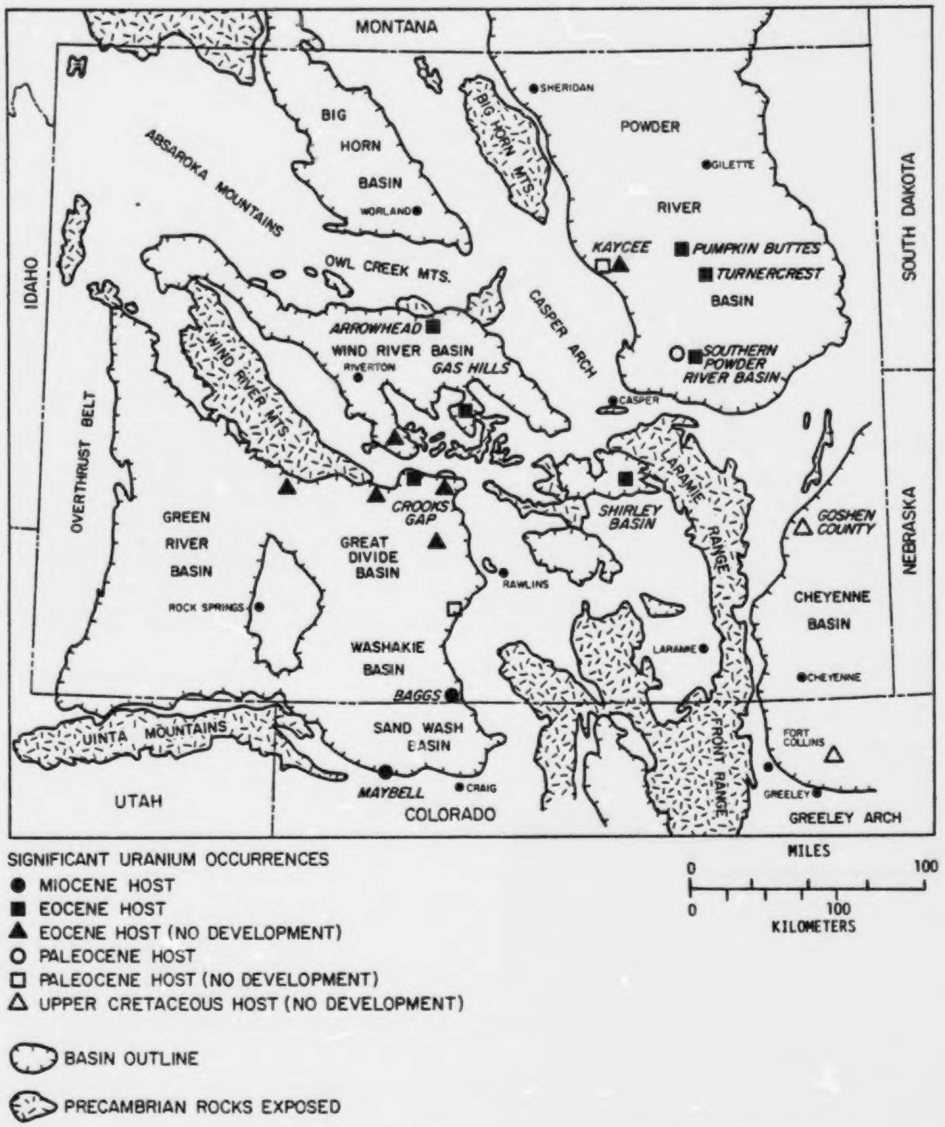
MONTANA
SHERIDAN
POWDER
RIVER
BASIN
BIG
HORN
BASIN
WORLAND
BIG HORN MTS.
GILETTE
ABSAROKA MOUNTAINS
OWL CREEK MTS.
KAYCEE
PUMPKIN BUTTES
TURNERCREST
SOUTH DAKOTA
IDAHO
CASPER ARCH
ARROWHEAD
WIND RIVER BASIN
RIVERTON
GAS HILLS
SOUTHERN POWDER RIVER BASIN
WIND RIVER MTS.
CASPER
OVERTHRUST BELT
LARAMIE RANGE
CROOKS GAP
SHIRLEY BASIN
GOSHEN COUNTY
NEBRASKA
GREEN
RIVER
BASIN
GREAT
DIVIDE
BASIN
RAWLINS
CHEYENNE
BASIN
ROCK SPRINGS
WASHAKIE
BASIN
LARAMIE
CHEYENNE
BAGGS
UINTA MOUNTAINS
SAND WASH
BASIN
FORT COLLINS
MAYBELL
CRAIG
FRONT RANGE
GREELEY
UTAH
COLORADO
GREELEY ARCH
SIGNIFICANT URANIUM OCCURRENCES
● MIOCENE HOST
■ EOCENE HOST
▲ EOCENE HOST (NO DEVELOPMENT)
○ PALEOCENE HOST
□ PALEOCENE HOST (NO DEVELOPMENT)
△ UPPER CRETACEOUS HOST (NO DEVELOPMENT)
BASIN OUTLINE
PRECAMBRIAN ROCKS EXPOSED
MILES
0
100
0
100
KILOMETERS

Figure 19. Uranium Deposits in the Wyoming Basins (DeVoto, 1978)

pyritic gray sandstone. Oxide staining is marked within the Powder River Basin but subtle in the Gas Hills and Shirley Basin.

Other formations in Wyoming with reported uranium reserves include the Teapot Sandstone Member of the Cretaceous Mesaverde Formation along the southwestern flank of the Powder River Basin, the Cretaceous Louise Formation in the northeastern portion of the Powder River Basin and the Miocene Browns Park Formation in the Washakie and Sand Wash Basins. Known mineable reserves in Wyoming also occur in the Hanna, Big Horn, and Green River Basins.

Deposits in South Dakota--

The only significant uranium production in South Dakota has come from the Southern Black Hills district, a portion of the larger Inyan Kara belt of mineralization along the southeast flank of the Black Hills (Figure 20).

The uranium mineralization occurs in the Lower Cretaceous Inyan Kara Group which consists of interbedded fluvial and marine-fluvial sandstones. The bulk of the reserve is restricted to a single deposit, the Harber Mine, containing 600,000 tons of uranium ore with an average grade of 0.23% U_3O_8. Ores are localized in the basal Dakota Sandstone Formation, just above its contact with the underlying Morrison Formation. The Dakota is a fluvial, carbonaceous, arkosic sandstone.

The major deposit is tabular in shape with an average thickness of 1.2-1.8 m (4 to 6 feet), although thicknesses of 3.7 m (12 ft.) are not uncommon. Uraninite and coffinite are the principal ore minerals. Genesis of the ores is thought to be related to uplift of the Black Hills during the Oligoecene Epoch, subsequent leaching of tuffaceous beds by groundwater, and deposition of leached uranium in a reducing environment in the Inyan Kara Group.

Deposits in New Mexico---

The major unranium-producing mines in New Mexico lie within the 137 km (85 mi.) long Grants Mineral Belt in the northwestern corner of the state, with the bulk of the production coming from the Ambrosia Lake and Laguna districts (Figure 21). The Grants District lines within the Colorado Plateau physiographic province.

The Colorado Plateau is a region of uplifted sedimentary igneous and volcanic rocks which range in age from Precambrian through Tertiary. The Plateau was tectonically stable during much of the Paleozoic. Deformation, beginning in the Pennsylvanian Period, form the Zuni uplift. Detritus shed by the uplift filled the San Juan Basin to the north. Rejuvenation during the Cretaceous Laramide orogeny resulted in the deposition of additional sediments in the San Juan Basin.

The uranium occurs predominantly in terrestrial sandstone of the upper part of the Morrison Formation of Jurassic age, but less important deposits are found in the Todilto Limestone (Jurassic) and Dakota Formation (Cretaceous). The major producing horizons in the Morrison (the Westwater Canyon and Jackpile Sandstone) are fluvial, lenticular, quartzose or arkosic sandstone interbedded with claystone and mudstone. The sandstones are paleochannel systems ranging in width from tens of feet to many miles.

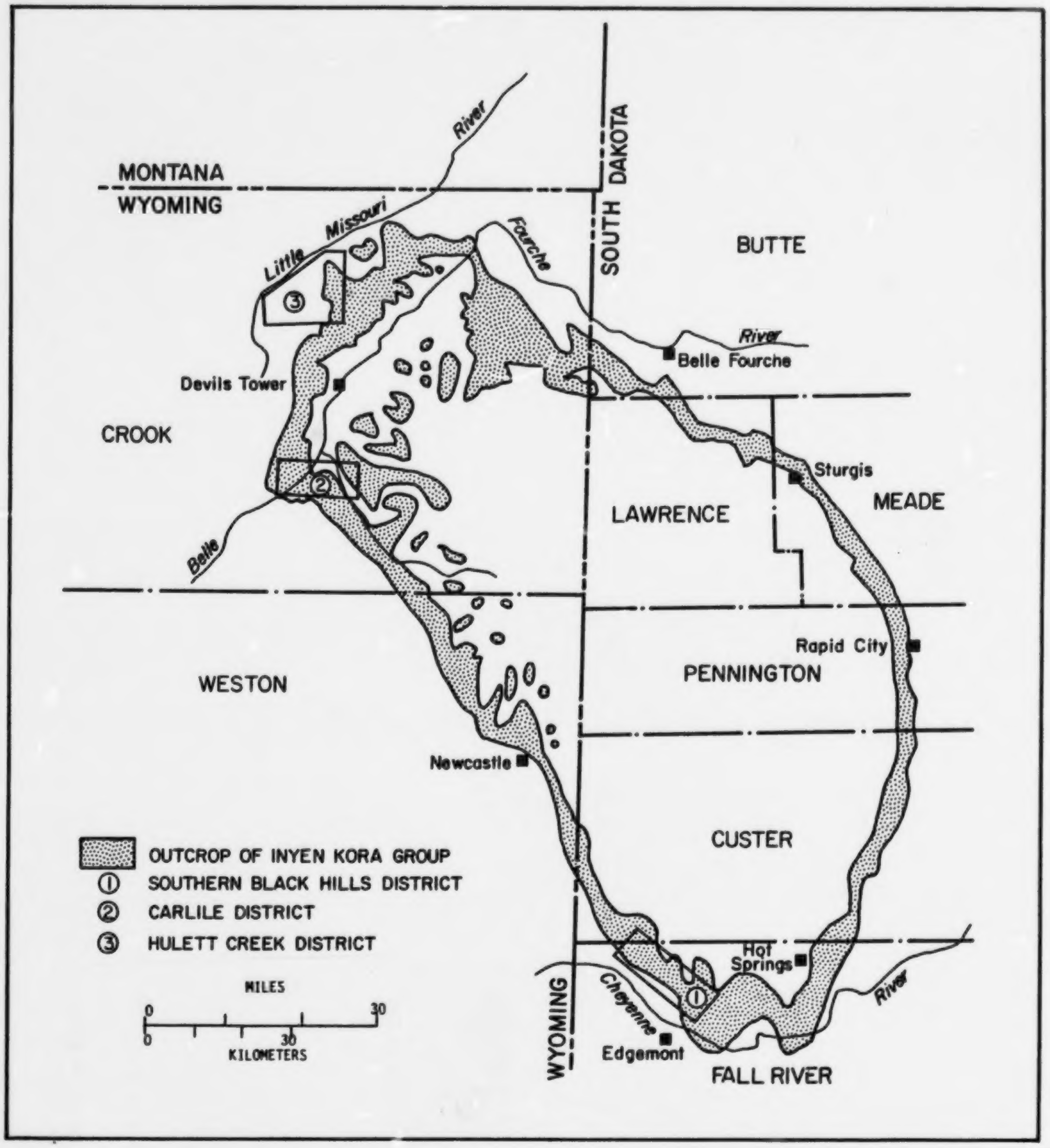
MONTANA
WYOMING
SOUTH DAKOTA
Little Missouri River
Fourche
Belle Fourche River
Belle
BUTTE
Belle Fourche
Devils Tower
CROOK
Sturgis
MEADE
LAWRENCE
Rapid City
PENNINGTON
WESTON
Newcastle
CUSTER
Hot Springs
Cheyenne River
WYOMING
Edgemont
FALL RIVER
③
②
①
OUTCROP OF INYEN KORA GROUP
① SOUTHERN BLACK HILLS DISTRICT
② CARLILE DISTRICT
③ HULETT CREEK DISTRICT
MILES
0
30
0
30
KILOMETERS

Figure 20. Uranium Deposits in the Southern Black Hills (Hart, 1968)

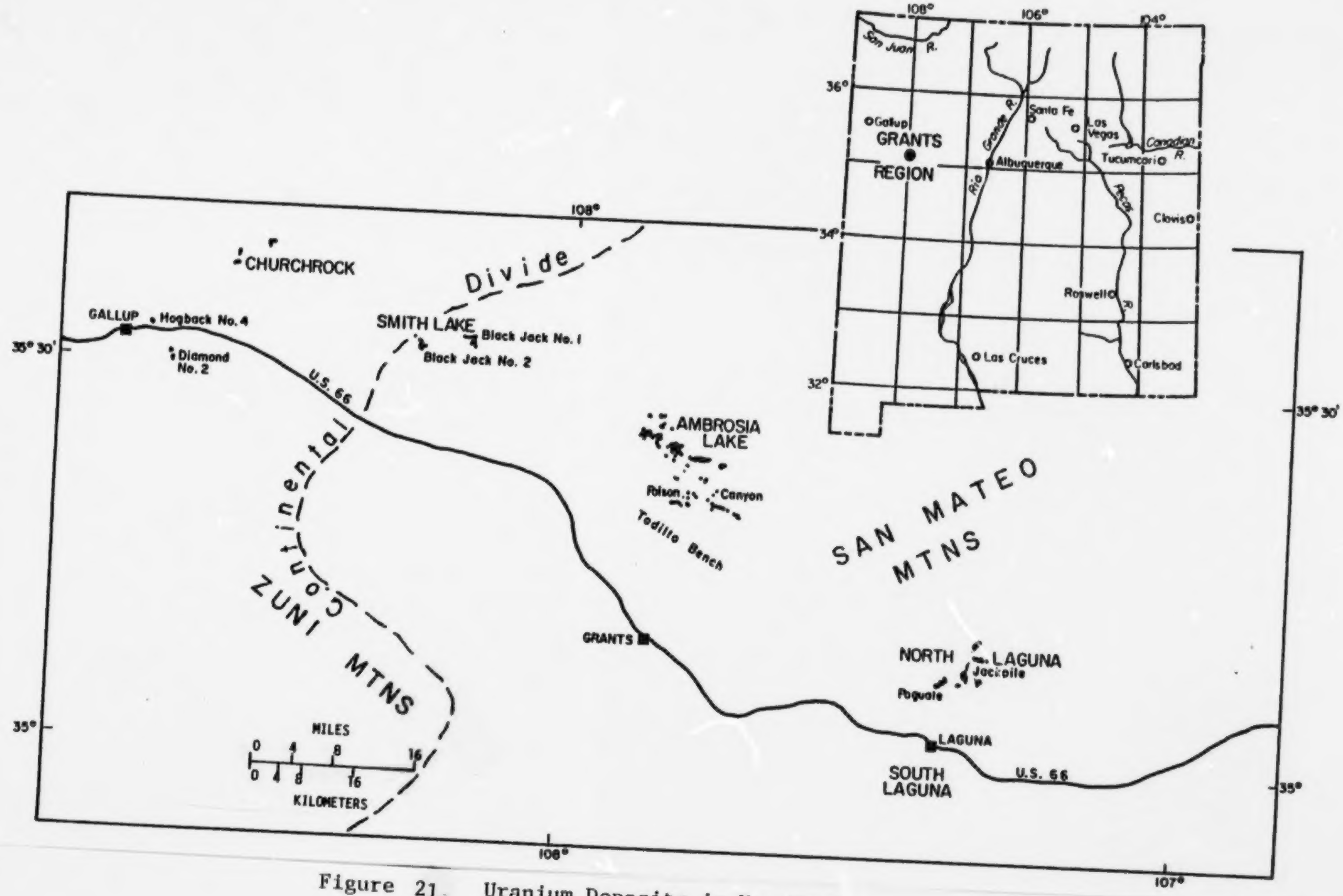
108°
106°
104°
San Juan R.
36°
Gallup
GRANTS
REGION
Rio Grande R.
Santa Fe
Las Vegas
Albuquerque
Canadian R.
Tucumcari
Pecos R.
Clovis
34°
Roswell
Las Cruces
Carlsbad
32°
108°
CHURCHROCK
Continental Divide
GALLUP
Hogback No. 4
Diamond No. 2
35° 30'
SMITH LAKE
Black Jack No. 1
Black Jack No. 2
U.S. 66
AMBROSIA LAKE
Poison
Canyon
Todilto Bench
SAN MATEO MTNS
ZUNI MTNS
GRANTS
NORTH
LAGUNA
Jackpile
Paguate
LAGUNA
SOUTH LAGUNA
U.S. 66
35°
MILES
0 4 8 16
0 4 8 16
KILOMETERS
35° 30'
35°
108°
107°

Figure 21. Uranium Deposits in New Mexico (Kelley, et al., 1968)

The uranium is disseminated in the sandstone. The average grade is 0.20 to to 0.30% U_3O_8 and deposit size varies from a few hundred tons to several million tons. The ore consists mainly of uraninite, coffinite and secondary oxides, including carnotite and uranophase.

The history of the Grants District ores is complex. At Ambrosia Lake, two principal stages of ore formation are recognized, separated by Laramide faulting. It is generally agreed that the original ores were deposited during the Cretaceous by groundwaters moving down dip from eroded volcanic and sedimentary rocks. Subsequent oxidation, particulary during the Quaternary, has significantly modified many deposits.

Deposits in Arizona--

Uranium mining areas in Utah and Northern Arizona are limited to four districts (Figure 22). Of these, only the Lisbon Valley District has recorded significant production. The uranium generally occurs in disseminated form in sandstone but in the Grand Canyon District it is found in breccia pipes. The age of host rocks varies from Triassic to Upper Permian, the older host rocks lying to the southwest.

The Lisbon Valley or Big Indian District is an arcuate belt of scattered deposits 15 miles in length, lying on the southwest flank of the Lisbon Valley anticline. The uranium deposits range in size from 500 to 1,500 tons and have an average grade of 0.35% U_3O^8. Uraninite is the principal uranium mineral. Ore bodies average 2 m (6 feet) thick, are tabular, amoeba-shaped masses and are concordant to bedding.

The host rock for the ores is the Moss Back Member of the Chinle Formation, a fluviatile, calcareous arkosic sandstone. Coalified plant material occurs in sandy lenses and pockets above the basal portion of the sandstone.

The uranium ore deposits are thought to have formed during the Triassic Period. Anticlinal uplift (of the ancestral Lisbon Valley anticline) resulted in deposition of the fluvial clastics of the Chinle Formation, of Triassic age, along the flanks of the anticline. Subsequent Triassic, Jurassic and Cretaceous sediments buried the Chinle to depths of several thousand feet. Uranium was leached from interbedded volcanics by oxidizing connate groundwaters and deposited downdip under reducing conditions. This emplacement occurred prior to the Laramide Orogeny, as evidenced by the fact that mineralized beds are offset by Tertiary faulting.

The Monument Valley-White Canyon District is situated in northeastern Arizona and southeastern Utah. Production from the district has been limited due to the small size of the ore bodies. Approximately half of them contain less than 1,000 tons of ore.

Most of the deposits are in an arcuate belt 5 to 19 km (3 to 12 miles) wide extending from Monument Valley northward nearly 209 km (130 miles). Uranium deposits are primarily restricted to favorable carbonaceous sandstone and con-

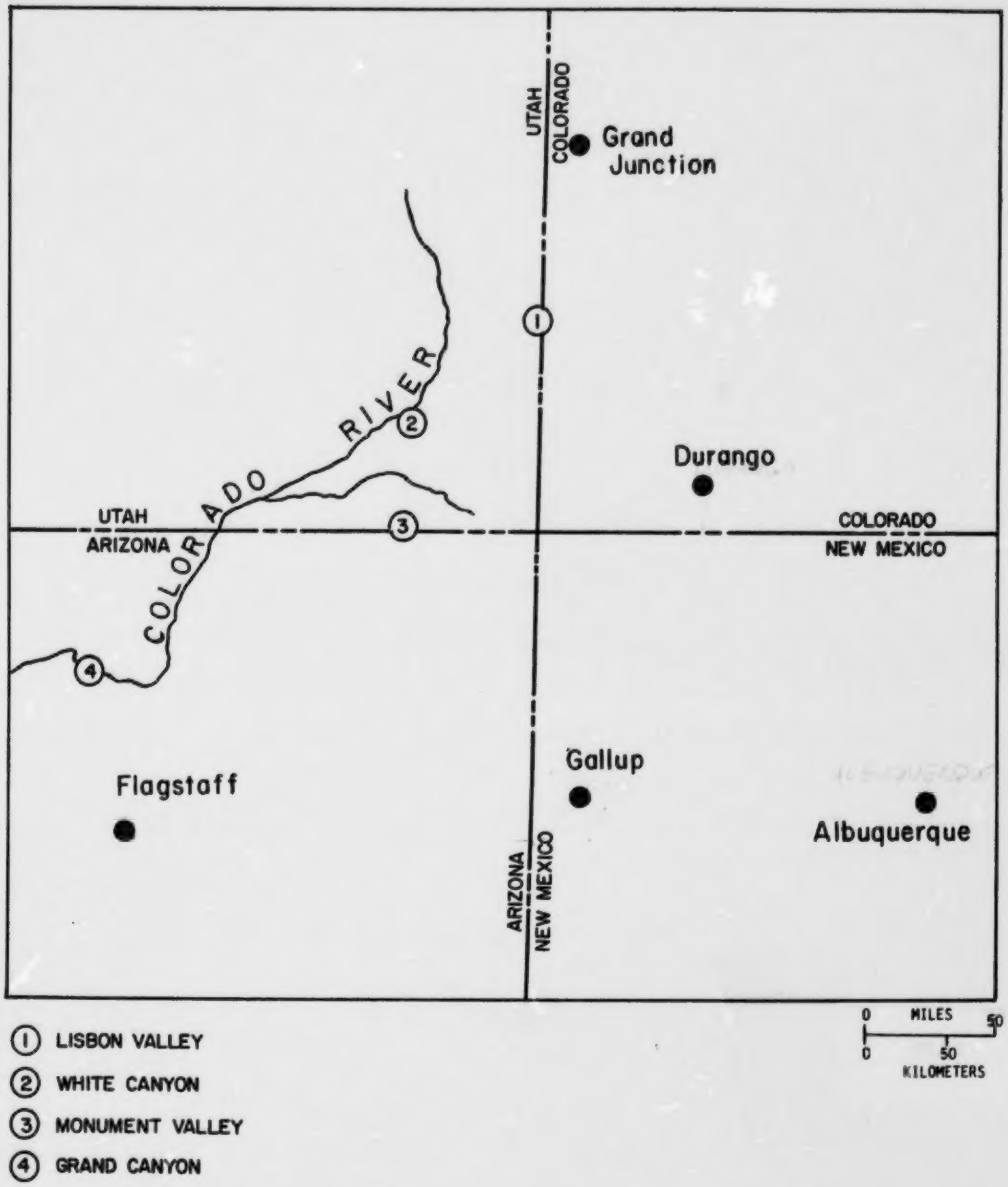
UTAH
COLORADO
Grand Junction
COLORADO RIVER
①
②
③
④
Durango
UTAH
ARIZONA
COLORADO
NEW MEXICO
Flagstaff
Gallup
Albuquerque
ARIZONA
NEW MEXICO
0 MILES 50
0 50 KILOMETERS
① LISBON VALLEY
② WHITE CANYON
③ MONUMENT VALLEY
④ GRAND CANYON

Figure 22. Uranium Deposits in Utah and Arizona

glomerate beds in the lower part of the Shinarump Member of the Chinle Formation. Ore deposits are generally linear to curvilinear in outline with lengths of a few feet to several thousand feet and the thickness of 0.3 to 3.7 m (1 to 12 feet). Uraninite and coffinite are the primary ore minerals. The average U_3O_8 grade is unreported, but vanadium (V_2O_5) averages 0.6% and copper 0.7%.

The ores occur in the Shinarump (the lowermost member of the Chinle), a fluvial-channel sandstone with interbedded lenticular siltstones and mudstones. Ore emplacement was similar to that described for the Lisbon Valley district.

Minor uranium production has also come from the Grand Canyon District of Arizona. Uranium-vandium ores in this district are localized in collapse structures in the Coconino and Supai Formations of Permian age. The collapse structures are circular in plan with diameters of a few feet to over 91m (300 feet). Uranium ore occurs as the cement for the breccia matrix commonly associated with sulfide mineralizations. Little is known of the genesis of this type of deposit and its limited areal extent has not made it a candidate for detailed study. This very small size of th breccia structures also limits to total reserve potential.

Minor production also comes from deposits in the Toreva Formation of the Black Mesa Basin, and the Dakota Sandstone in the San Juan Basin of Arizona.

Deposits in Colorado--

Much of the uranium production from Colorado has come from the Uravan mineral belt (Figure 23). This is a narrow north-northwesterly trending belt of deposits 97 km (60 miles) in length and 24 km (15 miles) in width. It is characterized by numerous ore bodies of relatively large size in close proximity to one another. The average grade of U_3O_8 is 0.27% and of V_2O_5 1.46%. Uraninite, coffinite and carnotite are the main uranium minerals, while vanadium-bearing chlorite and hydromicas are the major vanadium minerals.

The ore deposits occur principally in the uppermost sandstone unit of the Saltwash Member of the Mossison Formation of Jurassic age. This unit consists of sandstone lenses formed by a meandering, braided stream system. These lenses or channel fills are usually over 1.6 km (1 mile) in length and 15 m (50 feet) in thickness. The ore-bearing sands are generally fine to medium grain, composed predominantly of quartz with minor amounts of clay minerals, feldspar and heavy minerals.

The ore minerals are believed to have been precipitated from laterally migrating solutions. There is no apparent integral relationship between ore deposits and tectonic structural features, but some deposits do appear to be grouped in association with buried anticlinal folds.

Deposits in Texas--

Uranium was first discovered in South Texas in 1954. During the following decade and a half little interest was generated in the deposits, principally due to their low grade. In the 1970s, solution mining or uranium became economically feasible and the South Texas deposits began to receive considerable attention. Today, they have become a center of in situ solution mining study and are accounting for an increasing share of the annual U_3O_8 production of the nation.

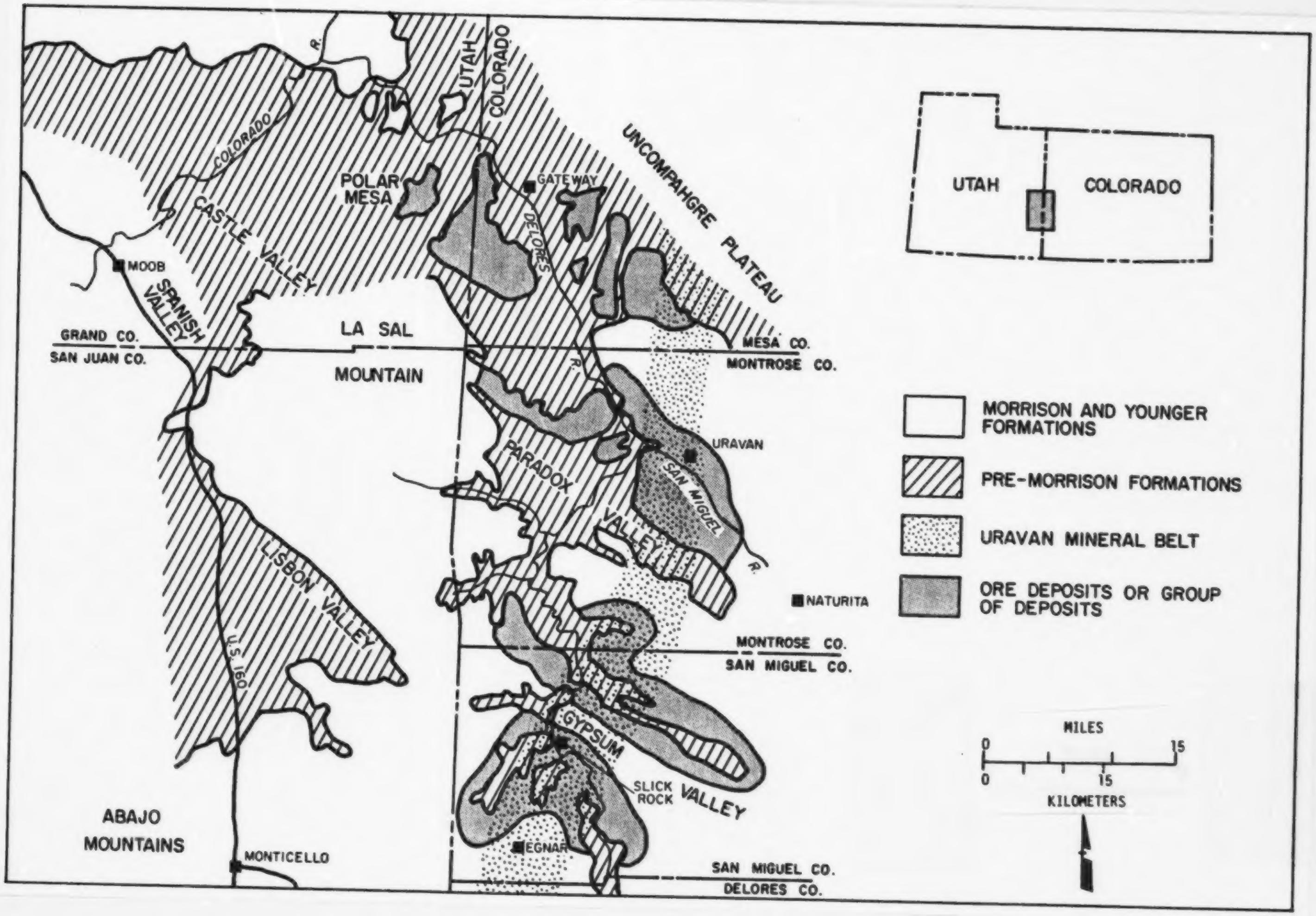
UTAH
COLORADO
UTAH
COLORADO
UNCOMPAHGRE PLATEAU
COLORADO
R.
POLAR MESA
GATEWAY
DELORES
R.
CASTLE VALLEY
MOOB
SPANISH VALLEY
GRAND CO.
SAN JUAN CO.
LA SAL
MOUNTAIN
MESA CO.
MONTROSE CO.
PARADOX
VALLEY
URAVAN
SAN MIGUEL
R.
NATURITA
LISBON VALLEY
U.S. 160
MONTROSE CO.
SAN MIGUEL CO.
GYPSUM
SLICK ROCK
VALLEY
EGNAR
ABAJO MOUNTAINS
MONTICELLO
SAN MIGUEL CO.
DELORES CO.
MORRISON AND YOUNGER FORMATIONS
PRE-MORRISON FORMATIONS
URAVAN MINERAL BELT
ORE DEPOSITS OR GROUP OF DEPOSITS
MILES
0
15
0
15
KILOMETERS

Figure 23. Uranium Deposits of the Uravan District

The uranium deposits occur in a belt of Eocene- to Pliocene-age rocks that stretch along the entire length of the Texas Gulf Coastal Plain (Figure 24). The Catahoula Formation of late Oligocene age is the major ore host.

The Catahoula Formation ranges in thickness from 61 m (200 feet) to 305 m (1,000 feet), thinning over the San Marcos Arch and thickening in the Houston and Rio Grande embayments. Most of the known deposits occur in the Rio Grande embayment. The fluvia system in the embayment (the Gueydan Fluvial System) is characterized by recognizable terrestrial, floodplain, and river channel facies. It differs from classic systems in the low sinuosity of the river channels. The ore deposits are usually associated with the thickest and coarsest sand sequences (channel-fill sands) but isolated deposits occur in sandy siltstone facies (crevasse splays).

Mineralization is typical roll front, redox boundary-controlled in the channel fill sands, but distinct relationships to redox boundaries are more difficult to establish for crevasse splay ore deposits. Fault zones appear to have some effect on localization of ore bodies but little or no effect on others.

Mineralization occurs as disseminated reduced uranium (coffinite) within medium- to fine-grained sand beds which contain mud lenses and abundant clay. The redox boundary is often ragged where clay content is higher. The thickest and more easily mineable ore bodies are restructed to sections that have well sorted sand and high sand-to-clay ratios

Ore bodies average 4.6 to 6.1 m (15 to 20 feet) in thickness, with lengths varying from hundreds of feet to thousands of feet. Ore grades are quite low, often less than 0.1% U_3O_8.

In addition to the aforementioned mining areas, minor production occurs from sandstone uranium deposits in the Permian Cutler Formation of the Paradox Basin, Utah.

Uranium Vein Deposits in Plutonic Rocks

Uranium production from vein deposits in plutonic rocks has not reached the proportions of that from sandstones; however, vein-type ores do constitute a small though significant share of the total production.

Uranium vein ores occur dominantly in felsic igneous rocks and metamorphic rocks, and the mineable veins are generally restricted to granitic rocks. The ores are deposited as open-space or fracture fillings along brecciated fault zones or in stockworks. The major ore mineral is pitchblende (fine-grained, botryoidal uraninite) with gangue minerals including quartz, calcite, and pyrite/marcasite. Wall rock alteration is limited, indicating low temperatures of deposition (i.e., <200° C.) A two-fold model is postulated to account for uranium in hydrothermal vein deposits. The uranium is thought to be derived originally from differentiation of MgO-CaO-deficient magmas and transported by hydrothermal solutions to dilation zones where reducing conditions caused precipitation. Later, oxidizing groundwaters dissolved some of the near-surface uranium and reprecipitated it at the redox boundary, causing the formation of a supergene enrichment zone.

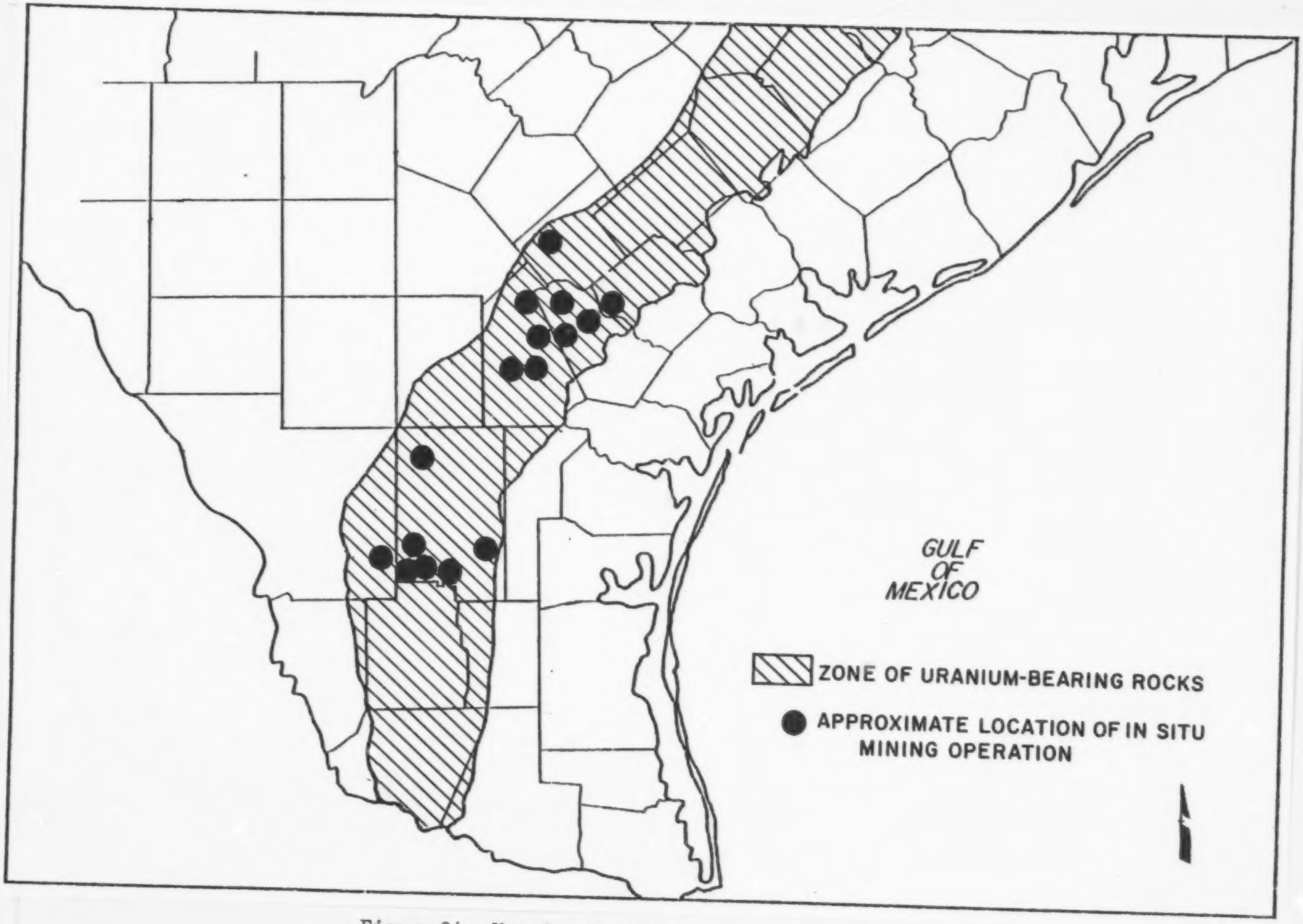
GULF OF MEXICO
▨ ZONE OF URANIUM-BEARING ROCKS
● APPROXIMATE LOCATION OF IN SITU MINING OPERATION

Figure 24. Uranium Deposits in South Texas

Colorado Mineral Belt--

The major uranium vein deposits are found in the Colorado Front Range. They occur in a thick sequence of complexly folded and metamorphosed, Precambrian sedimentary and volcanic rocks and granitic intrusions. The ore-stage mineralization appears to be related to early Tertiary hydrothermal activity associated with the granitic intrusions in the northeast-trending Colorado Mineral Belt (Figure 25). Localization of the vein ores was strongly influenced by the prevailing structural trends, northeast-trending Precambrian shear zones, north-northwest-trending Laramide faults and fracture zones, and east and northeast-trending folds in Precambrian metamorphic rocks.

The mineable uranium vein orebodies are concentrated in the east-central Front Range as open space fillings along fractures and faults. The veins occur within certain preferred host horizons which are characterized by brittleness (i.e., they are easily fractured) and anomalous pyrite or graphite content (indicating the presence of reducing environments). The Schwartzwalder Mine is the largest and most extensively studied of the vein-deposit reserves, where the ore occurs as brecciated vein fillings which are estimated to exceed 9.1-11 million kg (20-25 million pounds) of U_3O_8 (DeVoto, 1978).

The richest ore usually occurs where fractures branch or dips change abruptly. Host rocks include graphitic, pyritic schists, gneiss, quartzite, and granite pegmatite. Uranium is thought to have been deposited by solutions carrying U^{+6} in saline, low temperature, aqueous brines which boiled at low temperatures and subsequently reacted with pyrite and graphite to precipitate UO_2.

Midnite District, Washington--

A second district which has recorded major production is the Midnite Mining District, Washington (Figure 26). Ore has been mined from the Midnite and Sherwood Mines with the Spokane Mountain deposit currently under development.

The ore occurs as vein deposits in Cretaceous age, quartz monzonite and metasedimentary rocks of Precambrian age. Mineralization is concentrated along shears and fractures within the intruded granite and the metamorphosed pelitic sedimentary rocks. Both reduced and oxidized minerals are present in the ores. Pitchblende is the dominant reduced uranium mineral while autunite, uranophase and phosphuranylite are common oxidized uranium minerals. Pyrite-marcasite and pyrrhotite account for as much as 3 to 5% of the ore.

Deposits in the Midnite District average 305 m (1,000 feet) in length and 30 m (100 feet) in width, with thicknesses varying from 0.31 m (1 foot) to over 12 m (40 feet). Ore grade fluctuates widely from 0.01% to 2.8% with averages of 0.25 to 0.30% U_3O_8.

Ore genesis is complex and as many as five periods of mobilization, transportation and concentration may have occurred. The uranium is thought to have been present initially as syngenetic accumulations, and subsequently to have been metamorphosed, intruded and retransported by groundwaters. Recent groundwater activity is thought to have concentrated the ores to their presently mineable state.

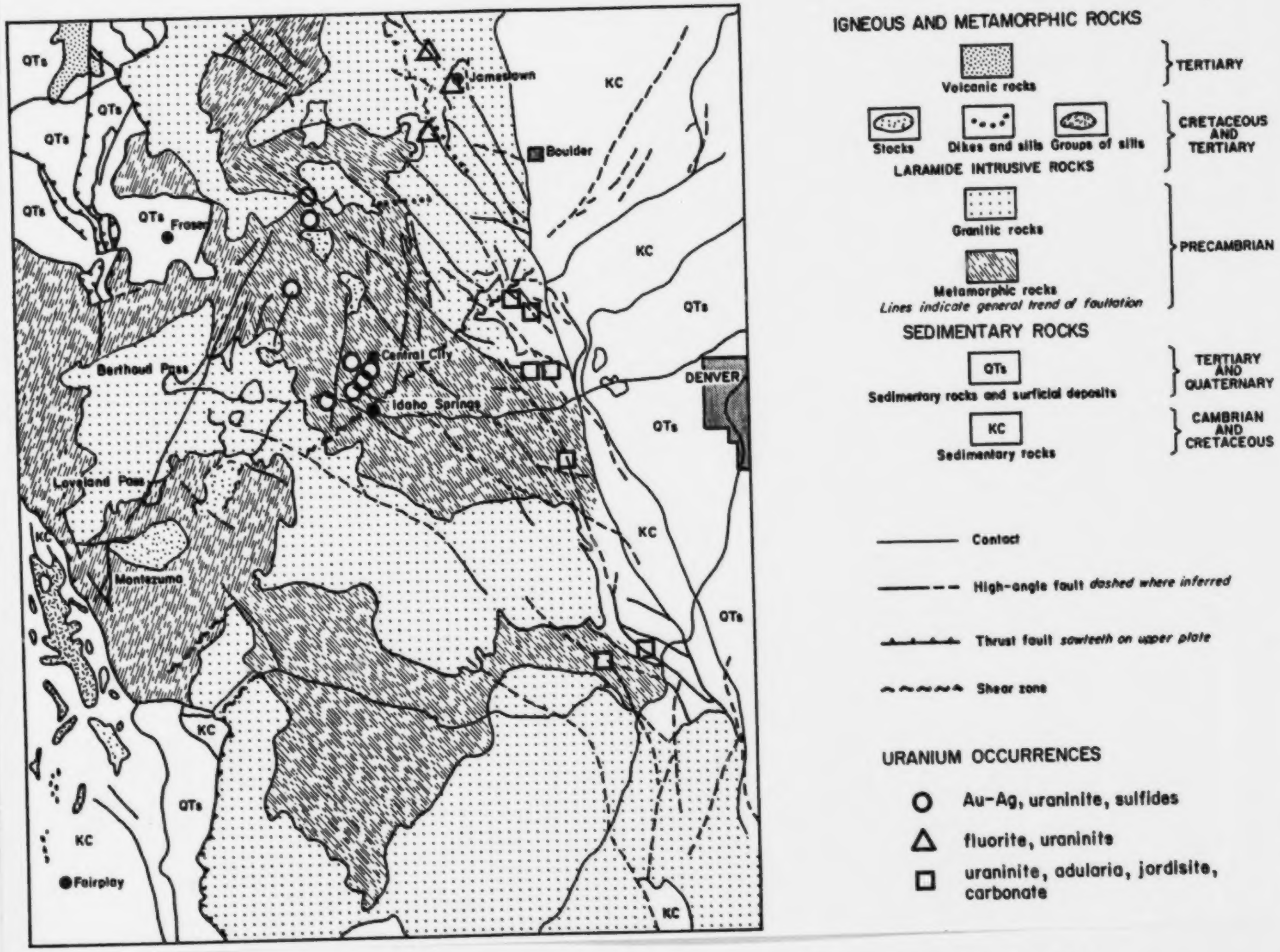
QTs
QTs
QTs
QTs
QTs
QTs
Fraser
Jamestown
Boulder
KC
KC
QTs
DENVER
QTs
KC
QTs
KC
Central City
Idaho Springs
Berthoud Pass
Loveland Pass
Montezuma
KC
KC
QTs
KC
Fairplay
IGNEOUS AND METAMORPHIC ROCKS
Volcanic rocks
TERTIARY
Stocks
Dikes and sills
Groups of sills
LARAMIDE INTRUSIVE ROCKS
CRETACEOUS AND TERTIARY
Granitic rocks
Metamorphic rocks
Lines indicate general trend of foliation
PRECAMBRIAN
SEDIMENTARY ROCKS
QTs
Sedimentary rocks and surficial deposits
TERTIARY AND QUATERNARY
KC
Sedimentary rocks
CAMBRIAN AND CRETACEOUS
Contact
High-angle fault dashed where inferred
Thrust fault sawteeth on upper plate
Shear zone
URANIUM OCCURRENCES
Au-Ag, uraninite, sulfides
fluorite, uraninite
uraninite, adularia, jordisite, carbonate

Figure 25. Uranium Deposits in the Colorado Mineral Belt
(De Voto, 1978)

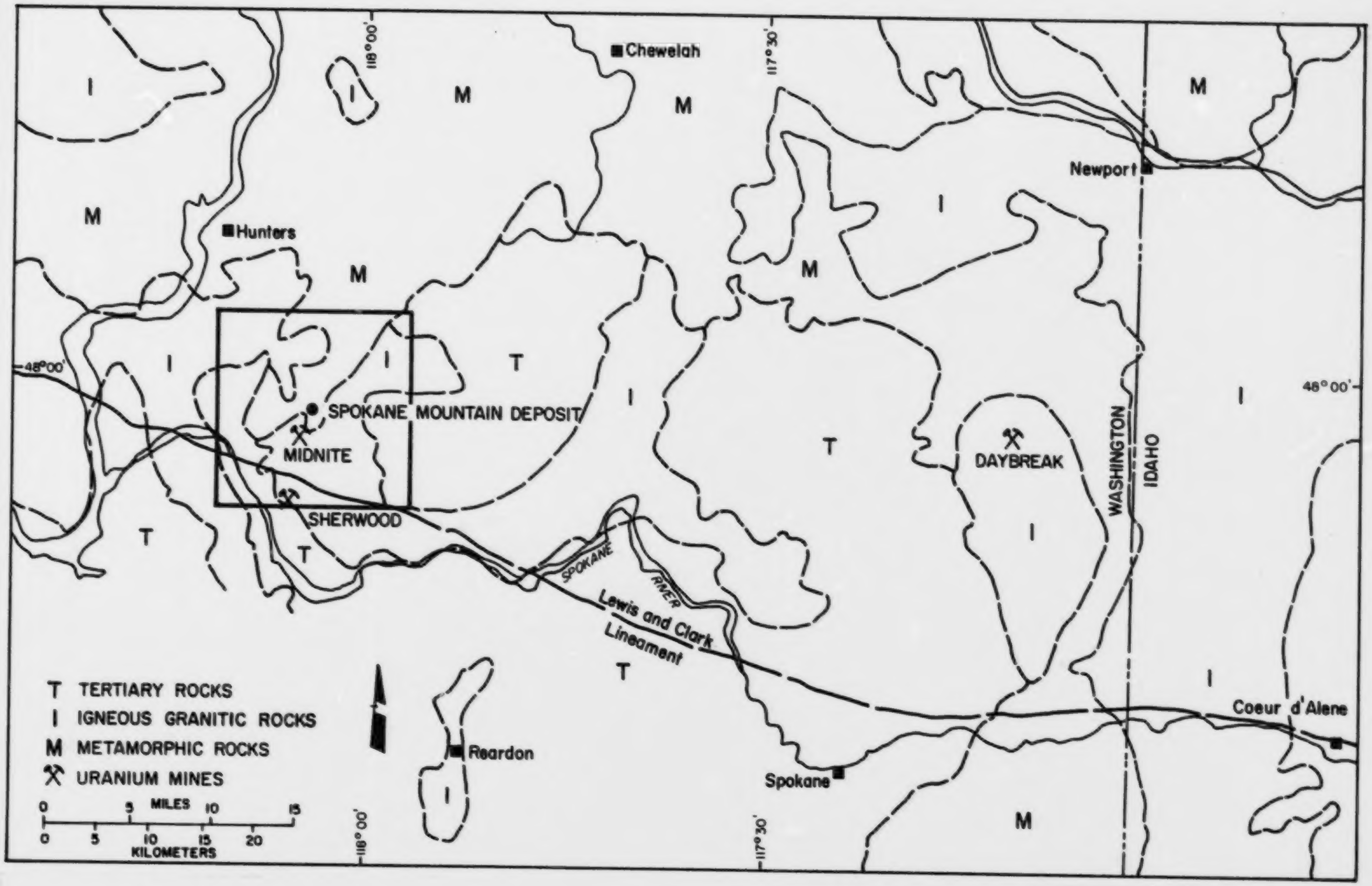
Chewelah
118°00'
117°30'
M
I
Newport
Hunters
48°00'
T
SPOKANE MOUNTAIN DEPOSIT
MIDNITE
SHERWOOD
DAYBREAK
WASHINGTON
IDAHO
48°00'
SPOKANE
RIVER
Lewis and Clark Lineament
Reardon
Spokane
Coeur d'Alene
T TERTIARY ROCKS
I IGNEOUS GRANITIC ROCKS
M METAMORPHIC ROCKS
⚒ URANIUM MINES
0 5 10 15 MILES
0 5 10 15 20 KILOMETERS

Figure 26. Uranium Deposits in the Midnite Mining District

Other Vein Deposits--

Other vein deposits occur in the Copper Mountain District of northwestern Wyoming, the Sawatch Mountains of central Colorado, the Marysville District, Utah, and the Bokan Mountain District, Alaska. Production from these districts is relatively small and the deposits are therefore not discussed here. In situ mining is not practiced in any of these districts.

A.2 ACTIVE OR PROPOSED IN SITU OR HEAP LEACH OPERATIONS

Known active or proposed leach-mining operations in the United States are listed in Table 24. These operations have been identified from information obtained by contacts with state licensing authorities and the U.S. Nuclear Regulatory Commission.

Table 24. Licensed Uranium Solution Mining Operations in the U. S.

State	Location or Mine	Type of License	Operator
Arizona	Miami	Heap leaching	Tom McClary
	S. Tucson	Heap leaching	Anamax Mining
Colorado	Maybell	Heap leaching	Union Carbide
	Naturita	Vat leach	Gates and Fox
	Grover	In situ	Wyoming Minerals-Power Resources
New Mexico	Crown Pt.	In situ Pilot plant	Mobil
	S. Trend-Grants	In situ Commercial Scale	Mobil
	L-Bar Ranch	In situ Pilot plant	Exxon
	Crownpoint	In situ License	Phillips
	Church Rock	Heap leach	United Nuclear
Oregon	McDermott, Nevada	In situ License	Placer AMAX
Texas	McBryde Mine	In situ; lic. issued	Caithness
	Trevino Mine	In situ; lic. issued	Conoco
	Hobson Mine	In situ; active	Everest
	Mt. Lucas Mine	In situ; lic. issued	Everest
	Las Palmas Mine	In situ; active	Everest
	Pawnee Mine	In situ; active	IEC
	Zamzow Mine	In situ; active	IEC
	O'Hern Mine	In situ; active	Mobil
	Holiday Mine	In situ; active	Mobil
	El Mesquite Mine	In situ; active	Mobil
	Piedre Lumbre Mine (3)	In situ; active	Mobil
	Brelum (2) Mine	In situ; active	Mobil
	Nell Mine	In situ; active	Mobil
	Karnes County	Heap Leach	Solution Engrg.
	Palangana Mine	In situ; active	Union Carbide
	Moser Mine	In situ; active	U.S. Steel
	Burns Mine	In situ; active	U.S. Steel
	Clay West	In situ; active	U.S. Steel
	Boots/Brown	In situ; active	U.S. Steel
	Pawelek	In situ; active	U.S. Steel
	Longoria	In situ; active	URI
	Benavides	In situ; active	URI
	Bruni	In situ; active	Wyo. Min. Corp.
	Lamprecht	In situ; active	Wyo. Min. Corp.
	Benham	In situ; lic. issued	Wyo. Min. Corp.
Washington	Ford, Washington	Pilot Plant	Dawn Mining
	Mt. Spokane	In situ lic. pending	Mineral Associates
Wyoming	Highland Mine	Commercial In situ	Exxon
	Fremont Co.	Commercial In situ	Ogle Petroleum
	Nine Mile Lake	Pilot In situ	Rocky Mtn. Energy
	Leuenberger Mine	Pilot In situ	Teton Exploration
	Irigaray Mine	Commercial In situ	Wyoming Minerals Corp.
	North Rolling Pin Site	Pilot In situ	Cleveland Cliffs
	Peterson Mine	Pilot In situ	Arizona Public Service Co.
	Charley Pty.	Pilot In situ	Cotter Corporation
	Johnson Co.	Pilot In situ	J & P Corporation
	Carbon Co.	Pilot In situ	Kerr-McGee
	Sweetwater Co.	Pilot In situ	Minerals Exploration
	Sundance Project	Pilot In situ	Nuclear Dynamics
	Reno Creek	Commercial In situ	Rocky Mtn. Energy
	Ruth Site	Pilot In situ	Uranerz U.S.A., Inc.
	Red Desert	Pilot In situ	Wold Nuclear
	Collins Draw	Pilot In situ	Cleveland-Cliffs
	Bill Smith Pty.	Pilot In situ	Kerr-McGee
	Willow Creek	Pilot heap leach	Cotter Corporation

February, 1981

APPENDIX B

PERTINENT FEDERAL AND STATE LAWS AND REGULATIONS

In this chapter, a list of laws and regulations that are applicable to solution mining and heap leaching of uranium is presented. These laws and regulations were identified from published Federal sources and by contacting responsible agencies in the states where unconventional extraction of uranium is going on or is contemplated.

B.1 FEDERAL LAWS AND REGULATIONS

Uranium Mill Tailings Radiation Control Act of 1978 (PL-95-502)

This Act, also referred to as the Mill Tailings Act, authorized the Department of Energy to enter into cooperative agreements with certain states to perform remedial actions involving residual radioactive materials at existing sites. The Act also amends the Atomic Energy Act of 1954 and gives NRC direct licensing authority over uranium mill tailings; prior to this enactment, tailings were controlled indirectly through licensing of mill operations (Nordhausen, 1980). By-product materials, which are defined as including wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, also are regulated by the Mill Tailings Act.

Other requirements of this regulation include obtaining an additional NRC license; conducting an environmental impact analysis if required for the permit application; and providing for the decontamination, decommission, and reclamation of sites at which ores were processed for their source content and at which by-product materials were deposited.

Safe Drinking Water Act of 1974 (PL-93-523)

The SDWA is of particular consequence to the in situ uranium leaching industry, specifically with regard to its Underground Injection Control (UIC) Program requirements. This provision requires that states develop UIC programs to protect their underground sources of drinking water from well injection practices and that they establish permit systems to authorize injection wells. Permitting of these wells has been incorporated into the Consolidated Permit regulations.

The UIC program is primarily intended to protect existing and potential groundwater sources for public water supplies. Public water supply systems include those that have at least 15 service connections or that serve a minimum of 25 persons. The quality of a potential groundwater source must be such that the water contains less than 10,000 mg/L TDS and that there is a sufficient yield (Riding, et al, 1979). There are provisions, however, that allow state program administrators to designate aquifers or parts thereof to be exempted from the regulations. An "exempted aquifer" might be identified if it were mineral producing, if the depth precluded the economical feasibility of pumping, or if the water were unfit for public consumption (Kasper, et al, 1979).

EPA categorized injection wells into five classes. Three of these types of wells could conceivably be used for extraction or disposal activities at an in situ uranium leach site:

- Class III wells are those used to inject fluids for the solution mining of minerals, for in situ combustion of fossil fuel, for sulfur mining by Frasch process, or for recovery of geothermal energy.
- Class IV wells are those used by generators of hazardous or radioactive wastes, or by owners or operators of hazardous waste management facilities or of radioactive waste disposal sites to dispose of these wastes into or above a formation which within one quarter mile of the well contains an underground source of drinking water.
- Class V wells are those injection wells not otherwise classified. (This includes deep well wastewater disposal at an in situ uranium leach site.)

Operators of permitted Class III wells must comply with requirements for continuous monitoring, quarterly reporting, well construction, and aquifer restoration, among others (Nordhausen, 1980). There is also a general prohibition against the migration of any injection fluid from a well into an underground source of drinking water.

EPA has established drinking water standards under the SWDA. Primary standards are enforceable; secondary standards are recommendations. Although these drinking water regulations do not specifically regulate in situ leaching, they may be considered by regulatory agencies when establishing groundwater restoration objectives. For example, a mine operator may be required to restore an aquifer to the baseline condition or to the EPA drinking water standards, whichever is less restrictive.

Energy Reorganization Act of 1974 (PL-93-438)

This Act amended the Atomic Energy Act of 1954 and established the U.S. Nuclear Regulatory Commission (NRC) as the agency responsible for issuing permits for uranium mines and mills. In situ uranium mines also are within NRC jurisdiction. For most of the states with know uranium reserves, NRC has delegated this permit-issuing authority to the states, which are referred to as "agreement states." In these states, in situ mine operators must apply to NRC for a source material license and to the state for a mine or mill permit; in non-agreement states, the miner must apply to NRC for the permits.

National Environmental Policy Act of 1969 (PL-91-190)

NEPA requires a detailed "environmental impact statement" (EIS) on actions significantly affecting the environment that involve Federal agencies or funds. The source material license from NRC or state regulations may require the preparation of an EIS for a proposed in situ uranium mining operation. To determine the necessity of an EIS, a mining applicant would submit an environmental report to the permitting agency for review. If the review indicates that the action may significantly affect the environment, an EIS would have to be prepared.

Federal Water Pollution Control Act Amendments of 1972 (PL-92-500)

This Act and its subsequent "Clean Water Act" amendments of 1977 have several provisons that might affect in situ uranium mining operations. Two requirements that could apply are:

- Obtainment of a permit, under the National Pollutant Discharge Elimination System (NPDES), for the discharge of pollutants into navigable waters.

- Compliance with Federal effluent limitations for specific pollutants in the ore mining industry category.

Prior to the operation of an in situ uranium mine and associated activities that will involve the discharge of pollutants into navigable waters, an NPDES permit must be obtained from EPA or the designated state water pollution control agency. The term, navigable waters, has a very broad definition which encompasses even surface drainage ditches and intermittent streams. NPDES permitting has been incoporated into EPA's "Consolidated Permit" regulation.

If contaminants are to be discharged to surface waters, then the effluent must meet the applicable EPA limitations. For conventional uranium mines and mills, the effluent guidelines for Ore Mining (40 CFR 400) apply. These set pollutant-specific daily maximums and monthly averages that are not to be exceeded. The provision, however, establishes a zero discharge standard for in situ uranium leaching. The effluent limitations are included in the NPDES permit, which basically establishes the conditions under which a discharge is permissible so that state water quality standards for the receiving waters will not be violated.

B.2 STATE LAWS AND REGULATIONS

Arizona

In Arizona, USNRC regulations cover primary mining and milling operations. State regulations are being formulated. Existing state regulations govern secondary processing operations.

California

California has no regulations that are specific for the mining and processing of uranium and USNRC regulations apply to such operations within the stace. Mining activities, including in situ mining, are governed by the California Surface Mining and Reclamation Act of 1975, administered by the State Mining and Geology Board. The California Environmental Quality Act of 1970, administered by the State Resources Agency, specifies requirements for environmental impact statements.

Colorado

Regulations that may be applicable to in situ mining include:

1) The Colorado Mined Land Reclamation Act, revised in December, 1980.

2) Rules and Regulations of the Radiation and Hazardous Waste Control Division, Colorado Department of Health; and

3) The Uranium Mill Licensing Guide, issued by the same organization. A representative of the Department of Lands stated that solution mining is governed more by policy than by specific laws.

Idaho

No regulations specific to the mining and processing or uranium exist in Idaho. The Idaho Department of Health and Welfare's Division of the Environment is responsible for the administration of the following rules and guidelines:

1) Technical Guide for Control of Water Pollution from Mining and Milling Operations;

2) Rules and Regulations for the Control of Air Pollution in Idaho; and

3) Water Quality Standards and Wastewater Treatment Requirements for Idaho.

Montana

The Montana Water Quality Act sets water quality standards and regulates the discharge of pollutants. This Act is administered by the State Department of Health and Environmental Science. The Department of State Lands administers the Strip and Underground Mine Reclamation Act of April 1, 1980, and regulations governing the reclamation of mined lands.

New Mexico

The New Mexico Environmental Improvement Agency, Division of Water Quality Control, administers the New Mexico Water Quality Control Act and the Environmental Quality Control Act. The regulations of the Water Quality Control Commission establish standards for ground and surface waters. The Radiation Protection Regulations of the radiation Protection Bureau of the State Department of Health apply to radiological aspects of uranium mining operations.

South Dakota

Existing regulations for this state are at present incomplete. Presently applicable regulations include the Surface Mining Land Reclamation Act; other aspects of uranium mining operations are governed by USNRC regulations.

Texas

The Texas Department of Water Resources administers the following regulations:

1) The Texas Water Code;

2) Texas Underground Injection Control Regulations; and

3) Texas Consolidated Waste Discharge Permit Regulations.

The Texas Department of Health Resources administers:

1) Radioactive Materials Licences

2) Regulations of the Radiation Control Branch for environmental assessment of in situ uranium mines.

These state agencies review proposed in situ operations and act to ensure that design, operation, and restoration requirements are met.

Utah

The State Department of Natural Resources, Division of Oil, Gas and Mining, administers:

1) The Oil and Gas Conservation Act;

2) The Mined Lands Reclamation Act;

3) General Rules and Regulations; and

4) Rules of Practice and Procedure to control underground and surface mining and drilling activities.

Washington

The State of Washington Department of Ecology administers the State Environmental Policy Act, and has issued Regulations Regarding the Stabilization of Uranium and Thorium Mill Tailings Piles. These regulations are currently undergoing review and are expected to be modified in the near future.

Wyoming

The State Department of Environmental Quality administers the Wyoming Environmental Quality Act, which governs solution mining and processing of uranium, as well as effects on the land, air, and water and solid waste management. Regulations of this Act are the responsibility of the three Divisions of Land, Air, and Water Quality, respectively. Water Quality Rules and Regulations of immediate concern to in situ mining operations are set forth in Quality Standards for Wyoming Ground Waters and Wyoming Ground Water Pollution Control Permit conditions, of the Division of Water Quality. Wyoming is not an agreement state and licenses to mine uranium there are obtained from the USNRC.